Year 2 Report on NASA Grant NNX16AC79G

Participating Scientist in Residence for the Venus Climate Orbiter/Akatsuki

INVESTIGATION OF THE VENUS WEATHER

From Venus Climate Orbiter (VCO) / Akatsuki Data

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1. Introduction

The Akatsuki orbiter began systematic collection of Venus observations in April 2016 following a successful orbit insertion on 7 December 2015 followed by a checkout period. All four imaging cameras have returned useful data and, the radio science experiment has conducted many radio occultations using the JAXA and Indian Deep Space Network facilities. The fifth camera on the Akatsuki orbiter (Lightning and Airglow Camera) has also been successfully operated during specific observing periods on the dark side of Venus.

For the purpose of the investigation of weather on Venus, the four imaging cameras provide the primary data, with the radio occultation profiles providing supplementary information on the thermal structure of the atmosphere for weather events near the occultation locations. These data are being archived by JAXA and also are being delivered to the NASA Planetary Data System.

Following modifications to the software previously developed to access the Akatsuki data, preliminary tests were conducted to verify the camera focal lengths and boresight alignment in accordance with the available spacecraft pointing information and ephemeris.

The progress made in Year two of this investigation is described below.

2. Akatsuki Data

The Akatsuki orbiter hosts four imaging cameras – UVI, IR1, IR2 and LIR, each one tailored for specific wavelength range. Thus, the UVI with two filters (283 and 365 nm) observes Venus at the ultraviolet to learn about the distribution and movements of the contrasts caused by SO2 and other unknown absorbers. The IR1 camera, images Venus at near infra-red on the day and night side of the planet at 0.97, 1.01 μm to probe the surface topography and the low level clouds. The IR2 camera images Venus at 2.02 μm on the day side to probe the Venus cloud deck at a wavelength where carbon dioxide (the main constituent of the Venus atmosphere) has an absorption band, thereby indicating cloud altitude differences and on the night side at 1.74, 2.26 and 2.32 μm to investigate the mid-cloud layer of Venus. Finally, the LIR camera obtains cloud top temperature differences globally. Figure 1 shows some examples of the images.

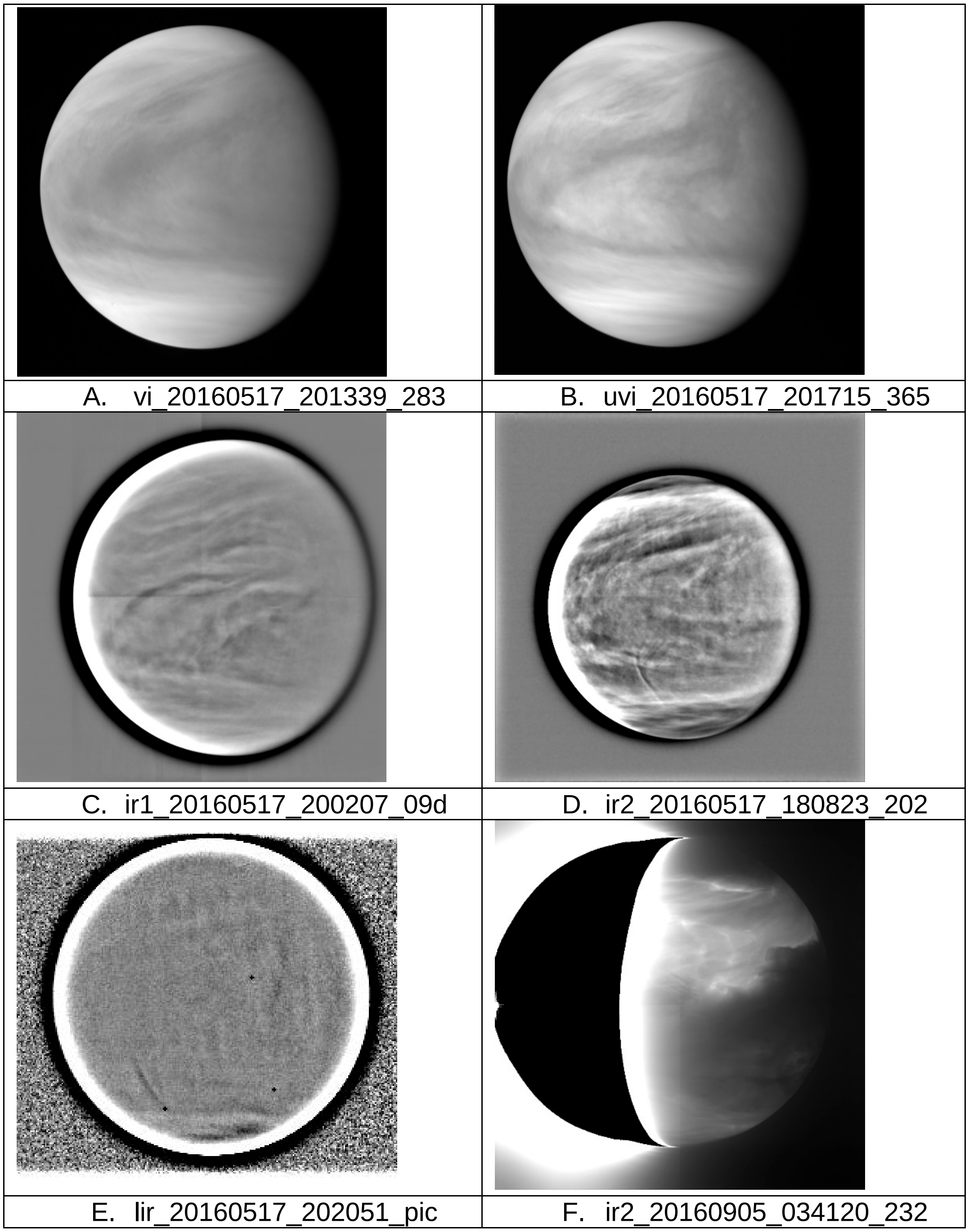


Figure 1. A selection of images taken from Akatsuki cameras. The date, time and filter are noted below each image. Day side images (A through E) were taken on 17 May 2016 while F is a night side image (IR2 camera) taken on 5 September 2016. Images A and B are from the UVI camera at 20:13:39 (283 nm) and 20:17:15 UT. Image C is taken from IR1 camera (0.9 μm) on the same day at 20:02:07 UT while image D is from the IR2 camera (2.02 μm) acquired at 18:08:23 UT. Images C and D are shown in high-pass filtered versions to bring out detail. Image E is from the LIR (8-12 μm) camera taken at 20:20:51 UT. The night side image (F) is taken through the 2.32 μm filter. At 2.26 and 1.74 μm, Venus appears similar.

Several new phenomenon were observed in the nightside images of Venus acquired by the IR 2 camera, such as the classical "mushroom" organization, analogous to formations routinely observed in terrestrial water vapor images from geosynchronous weather satellites, which have been shown to be mesoscale cyclonic and anticyclonic circulations (Houghton & Suomi, 1978; Martín et al., 1999), frontal boundaries, and stationary gravity waves that appear to be triggered by topography. The cloud features seen in all camera data enable determination of cloud motions and an equatorial jet has been detected from the night side measurements. A paper of which I am a co-author, has been published in Nature Geoscience (Horinouchi et al., 2017).

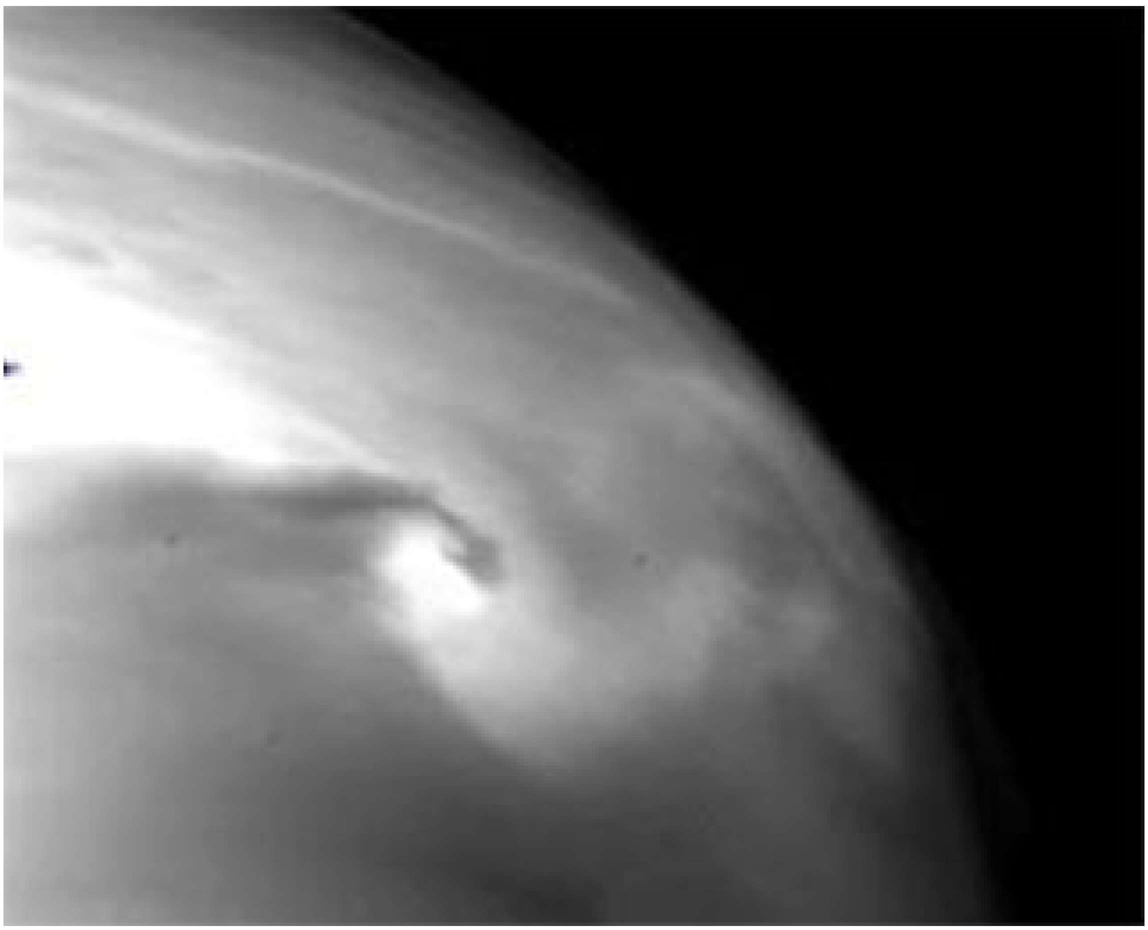


Figure 2. A "mushroom" feature was noticed in images from the IR2 camera taken on 7 May 2016 at 1.74, 2.26 and 2.32 μm. A search for similar formations revealed that a similar feature was observed in a similar location two orbits earlier, on 25 April 2016. This shape is seen commonly in water vapor channel images of Earth from weather satellites and the "mushroom" shape has been shown to be a result of a pair of anti-cyclonic and cyclonic circulations. The detection of such meso scale vortices on Venus is striking, raising questions about the creation of vorticity and the departures from the zonal nature of the atmospheric circulation on a slowly rotating planet.

2.1 Investigations

One of the primary tools for detecting weather on Venus is the morphology of the clouds, both on the day in reflected sunlight images and night side when the images are acquired in the near infrared radiation region (1 – 3 μm), that is emitted by the surface and the lower atmosphere below the cloud bottom (~ 47 km) from IR1 and IR2 cameras. These features appear as silhouettes due to differential absorption by the clouds and hazes above the emission levels. However, the cause of these contrasts both on the day and night sides of the planet are still unknown. This led to two separate investigations, one exploring the possibility of microorganisms contributing to the absorption and contrasts in the clouds and the other one focusing on cloud morphology at different wavelengths on the day and night side and new phenomenon detected in the images. These investigations led to submission of two papers and one being prepared for publication at present.

2.1.1 Absorption of incident solar energy by the clouds

It has been known for some time that sulfur dioxide gas is present in the Venus atmosphere at many levels as well as above the clouds. The two UVI camera filters were chosen such that one of the wavelengths is in one of the absorption bands for sulfur dioxide (283 nm) while the other one (365 nm) is at the peak of cloud cover contrast magnitude, thereby enabling investigation of the presence of other absorbers of sunlight which still remain unknown (Esposito et al., 1983). Since at least two absorbers were postulated from the spectral dependence of albedo of Venus and the global cloud contrasts (Pollack, 1980; Travis, 1975), and sulfur dioxide being identified as one of the absorbers, much of the discussion in the literature has focused on the other "unknown" absorber. However, a new assessment of the available information suggests that there may be more than one absorber (Jessup and Limaye, 2017) and the possibility of some microorganisms contributing to the absorption on the day side as well as contrasts cannot be ruled out. This possibility has been explored further with colleagues with an astrobiology background and a paper titled "**Venus' Spectral Signatures and the Potential for Life in the Clouds"** by Limaye et al. has been submitted to Astrobiology Journal.

2.1.2 Cloud Morphology at different wavelengths from day and night images from Akatsuki cameras

In images acquired routinely by the earth weather satellites, Earth clouds show very similar morphology at all wavelengths from visible to thermal infrared. One exception is the water vapor band images which depict the "dry" regions of the low and mid atmosphere more distinctly than images acquired at other wavelengths (Figure 1).

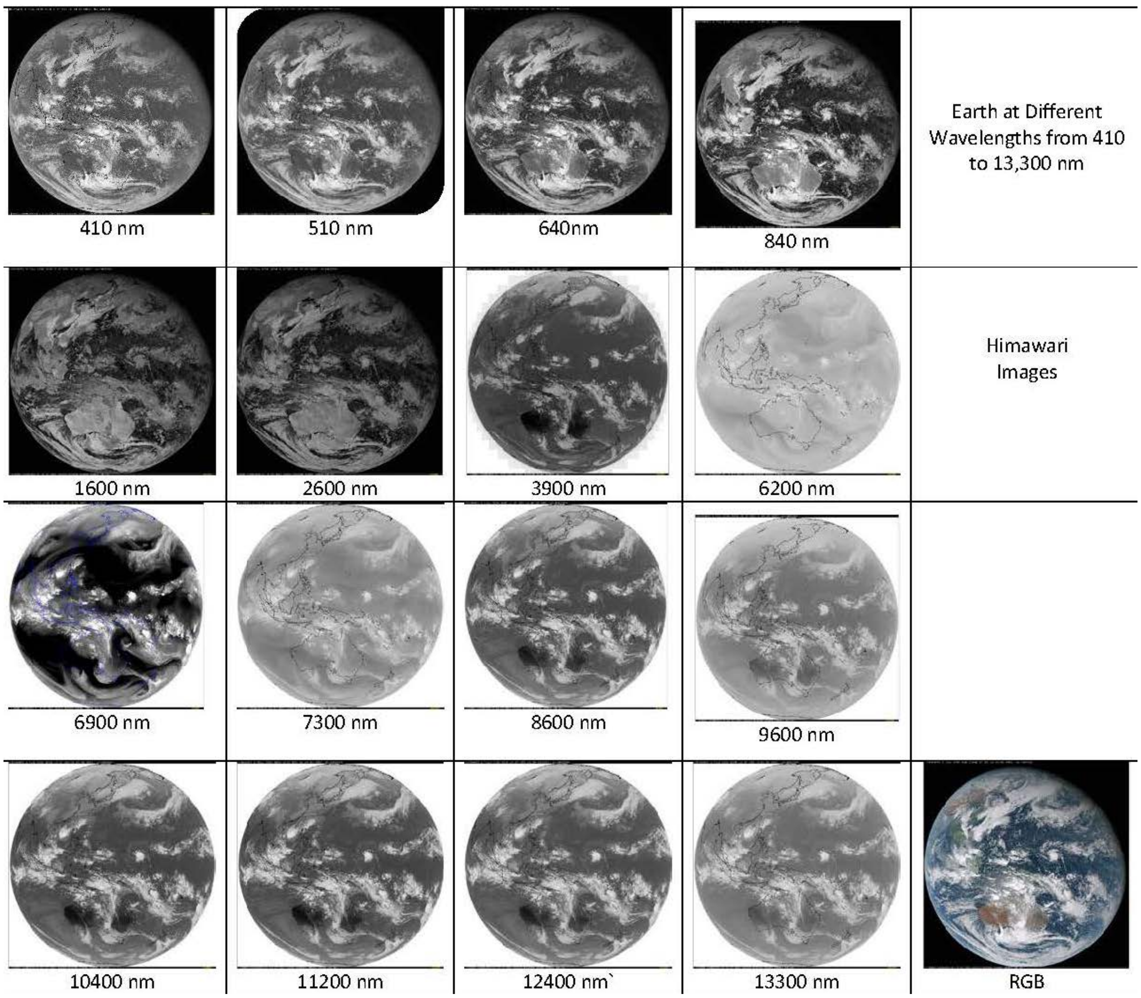


Figure 1. Earth images acquired by the Himawari weather satellite at different wavelengths showing the similarity of the cloud morphology.

In contrast, Venus appears remarkably different over the same wavelength range (Figure 2). This difference is due to the different composition of the Venus clouds at the atmosphere they evolve in and also the thickness atmosphere. The difference in the appearance of the Venus cloud features at different wavelengths highlight the complex chemical, physical and perhaps biological processes that determine the cloud structure. The morphology of the Venus cloud features observed by Akatsuki cameras has been described in a paper submitted to the Akatsuki Special issue of Earth, Planets and Space.

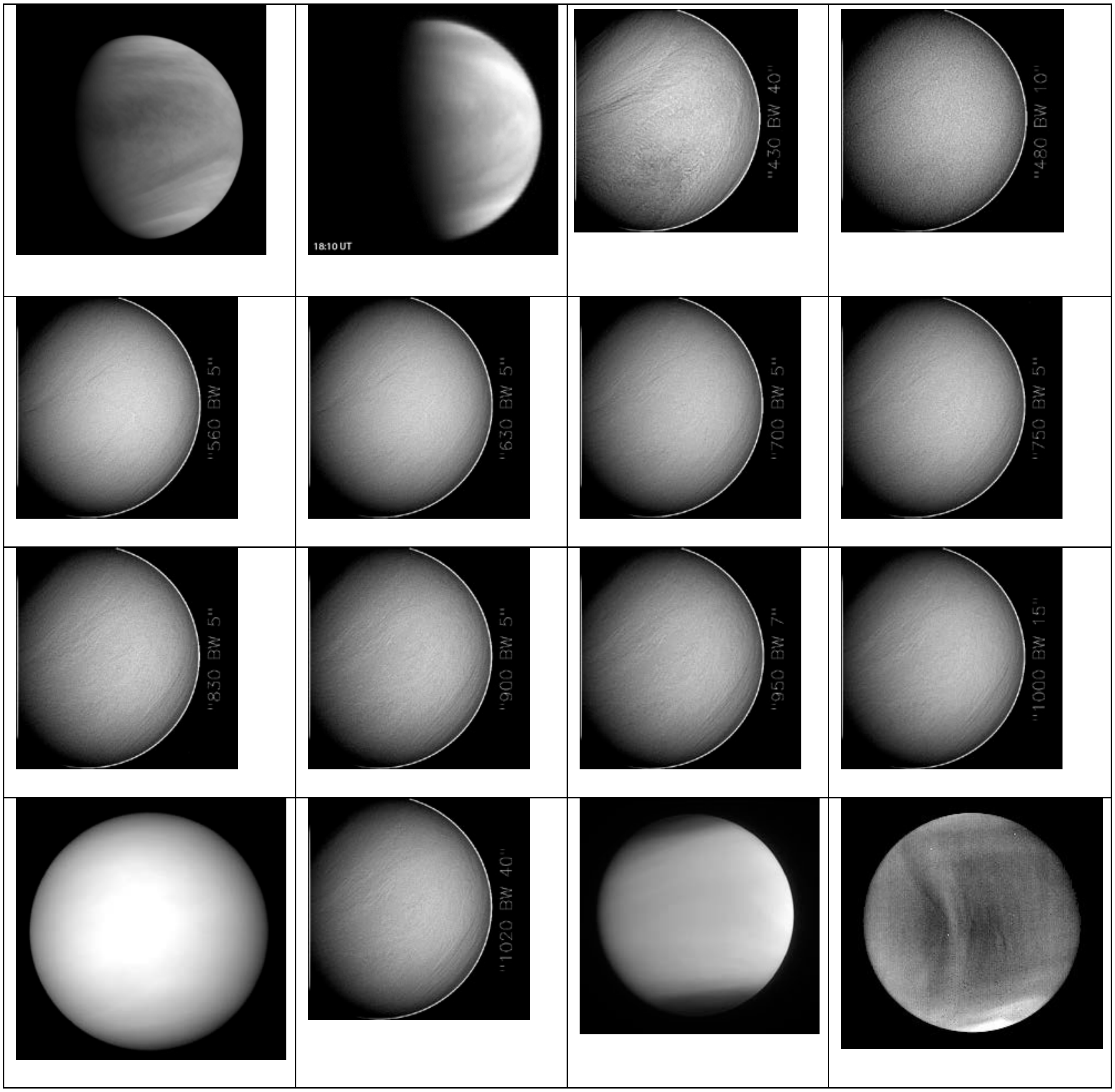


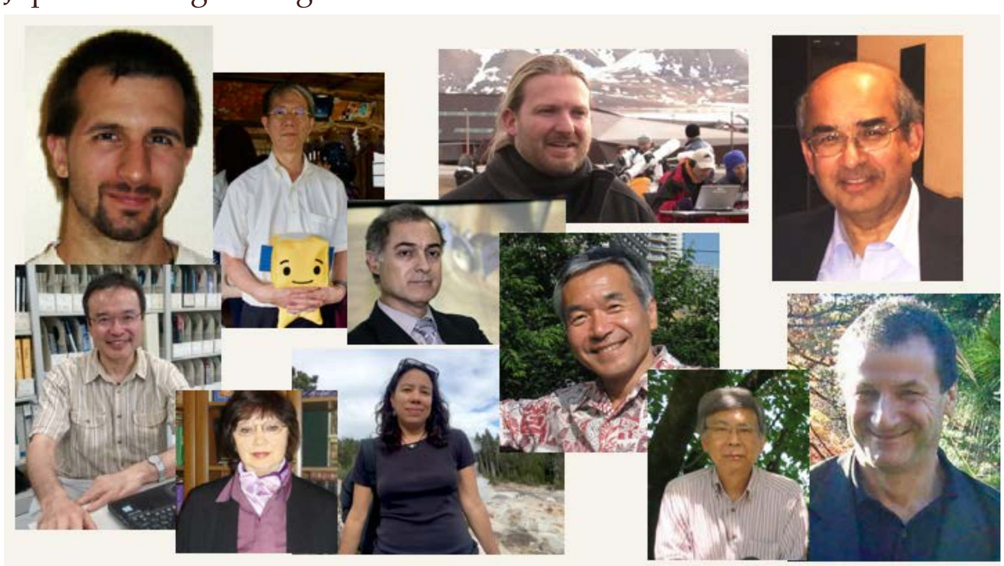
Figure 2. Venus at different wavelengths imaged by Akatsuki and MESSENGER cameras. Top row – (left to right) 283 nm, 365 nm (UVI Akatsuki), 430 nm, and 480 nm (MESSENGER –MDIS/WA). Second row – 560, 630, 700 and 750 nm (MDIS-WA). Third row- 830, 900, 950 and 1000 nm (MDIS-WA). Bottom row – 900 nm (IR1) 1020 nm (MDIS-WA), 2020 nm (IR2) and 10-14 µm (LIR). All MESSENGER images have been high pass filtered to bring out the very low contrast features.

2.1.3 Meso-scale vortex circulations in the IR2 images of Venus

The “mushroom” feature shown in Figure 2 was also observed two orbits earlier on 25 April 2016 and later in August. As indicated earlier, the morphology of the Venus features is very similar to such features seen in water vapor imagery. Unfortunately the data coverage from Akatsuki IR2 camera did not capture time sequences on the days when the features were discovered, and the time difference between the three filters in which the features are generally seen (Figure 3) is too short for any detection of vorticity within the features. A search for similar features in the same wavelength region (1.74 – 2.32 μm) revealed a few instances, but once again, time sequences as high resolution were not available. One key finding is that the features are found upstream of elevated topographic regions. A manuscript is being prepared documenting these findings and will be submitted for publication.

3. Akatsuki Venus International Conference

The Akatsuki project will host an international conference on Venus with support from the Fujihara Foundation, Japan as the 74th Fujihara Seminar: "Akatsuki" Novel Development of Venus Science during September 11-14, 2018 in Niseko, Hokkaido, Japan. An organizing team has been formed of which I am a member.



Science Organizing committee: Takehiko Satoh (Akatsuki, ISAS/JAXA) Masato Nakamura (Akatsuki, ISAS/JAXA) Yoshiyuki Hayashi (Theory/Modeling, CPS/Kobe Univ.) Yoshihisa Matsuda (Modeling) Kevin McGouldrick (NASA PS) Sanjay Limaye (NASA PS) Colin Wilson (Modeling) Thomas Widemann (Ground-based) Agustin Sánchez-Lavega (Cloud tracking) Martha Gilmore (Surface) Ludmila Zasova (Russian mission, IKI). URL: https://www.cps-jp.org/~akatsuki/pub/venus2018/

4. Akatsuki Science Working Team Meetings

There were three Akatsuki Science Working Team meetings held during 2017, in January 2017, April 2017, and July 2017 at ISAS/JAXA in Sagamihara, Japan. I participated in all three meetings and provided progress reports. The 7th meeting will be held during November 9-11, 2017.

5. PUBLICATIONS and Presentations

The following papers were published during this reporting period:

1. Horinouchi, T., Murakami, S.-Ya, Satoh, T., Peralta, J., Ogohara, K., Kouyama, T., Imamura, T., Kashimura, H.., **Limaye, S. S**., McGouldrick, K., et al. (2017a). Equatorial jet in the lower to middle cloud layer of Venus revealed by Akatsuki. Nature Geoscience, advance online publication. doi:10.1038/ngeo3016
2. T. Imamura, H. Ando, S. Tellmann, M. Pätzold, B. Häusler, T. M. Sato, Katsuyuki Noguchi, Yoshifumi Futaana, Janusz Oschlisniok, S. Limaye, R.K. Choudhary, Y. Murata, H. Takeuchi, C. Hirose, T. Ichikawa, T. Toda, A. Tomiki, T. Abe, Z. Yamamoto, H. Noda, T. Iwata, S. Murakami, T. Satoh, T. Fukuhara, K. Ogohara, K. Sugiyama, H. Kashimura, S. Ohtsuki, S. Takagi, Y. Yamamoto, N. Hirata, G. L. Hashimoto, M. Yamada, M. Suzuki, I. Nobuaki, T. Hayashiyama, Y. J. Lee, M. Nakamura, 2017. Initial performance of the radio occultation experiment 1 in the Venus orbiter mission Akatsuki, accepted for publication, Earth, Planets and Space. To appear in the Akatsuki special issue, late 2017.
3. Limaye, S. S., Lebonnois, S., Mahieux, A., Pätzold, M., Bougher, S., Bruinsma, S., et al. (2017). The thermal structure of the Venus atmosphere: Intercomparison of Venus Express and ground based observations of vertical temperature and density profiles☆. Icarus, 294, 124-155.Vandaele, A. C., Korablev, O.; Belyaev, D.; Chamberlain, S.; Evdokimova, D.; Encrenaz, Th.; Esposito, L., Jessup, K. L., Lefèvre, F., **Limaye, S.**, et al. (2017a). Sulfur dioxide in the Venus atmosphere: I. Vertical distribution and variability. Icarus, 295, 16-33.
4. Vandaele, A. C., Korablev, O., Belyaev, D., Chamberlain, S., Evdokimova, D., Encrenaz, Th., Esposito, L., Jessup, K. L., Lefèvre, F., **Limaye, S**., et al. (2017b). Sulfur dioxide in the Venus Atmosphere: II. Spatial and temporal variability. Icarus, 295, 1-15.

PAPERS UNDER REVIEW:

The following papers were submitted during the current reporting period for publication and are currently undergoing Peer Review:

1. S.S. Limaye, S. Watanabe, A.Yamazaki, M. Yamada, T. Satoh, T. M. Sato, M. Nakamura, M. Taguchi, T. Fukuhara, T. Imamura, T. Kouyama, Y. J. Lee, T. Horinouchi, J.Peralta, N. Iwagami, G.L. Hashimoto, S Takagi, S. Ohtsuki, S .Murakami, Y. Yamamoto, K.

Ogohara, H. Ando, K. Sugiyama, N. Ishii, T. Abe, C. Hirose, M. Suzuki, N. Hirata, E. F. Young, **Venus Looks Different at Different Wavelengths: Morphology of the Global Day and Night Cloud Cover at Different Wavelengths from Akatsuki Cameras**, *Submitted to Earth, Planets and Space.*

2. Limaye, S.S., R. Mogul, A.H. Ansari, G.P. Słowik, D.J. Smith, and P. Vaishampayan, **Venus' Spectral Signatures and the Potential for Life in the Clouds**. *Submitted to Astrobiology.*
3. Limaye, S.S., D. Grassi, A. Mahieux, A. Miglioriono, S. Tellmann, and D. Titov, Venus atmospheric trhermal structure and radiative balance. *Submitted to Space Science Reviews. To be included as Chapter 4 of Venus III (C. Russell, Chief Editor).*

CONFERENCE PRESENTATIONS

1. Bullock, M., S.S. Limaye, D.H. Grinspoon, and M.J. Way, The Effect of Bond Albedo on Venus' Atmospheric and Surface Temperatures. American Geophysical Union 2017 Fall meeting , New Orleans, 8-12 December 2017
2. Gero, J., S. Limaye, P. Fry, Y. J. Lee, G. Petty, J. Taylor, S. Warwick, An airborne spectrophotometer for investigating solar absorption on Venus, 14th VEXAG Meeting, Applied Physics Laboratory/Johns Hopkins University, Laurel, MD, 14-16 November 2017.
3. Jessup, K-L., R. Carlson, S. Perez-Hoyos, N. Ignatiev, Y-J. Lee, S. Limaye, F. P., Mills, L. Zasova, Motivations and Priorities for a Detailed In-situ Investigation of the Spatial and Temporal Variability of Venus' UV absorber, 8th Solar System Symposium, Space Research Institute (IKI), Moscow, Russia, 9-13 October 2017.
4. Jessup, K-L., R. Carlson, S. Perez-Hoyos, Y-J. Lee, F. P., Mills, S. Limaye, N. Ignatiev, L. Zasova, Motivations for a Detailed In-situ Investigation of the Spatial and Temporal Variability of Venus UV absorber, 14th VEXAG Meeting, Applied Physics Laboratory/Johns Hopkins University, Laurel, MD, 14-16 November 2017.
5. Limaye, S. S.; Jessup, K. L., Questions About Venus and Measurements Needed to Address Them from Future Missions to Venus, Lunar and Planetary Science Conference, the Woodlands, Texas, March 2017.
6. Limaye, S.; Słowik, G.; Ansari, A.; Smith, D.; Mogul, R.; Vaishampayan, P., Short wavelength albedo, contrasts and micro-organisms on Venus, European Geophysical Union, Vienna, Austria, April 2017.
7. Limaye, S.S., T. Satoh, T. Horinouchi, J. Peralta and T. Imamura, Mesoscale vortices on Venus, Japan Geophysical Union Meeting, Chiba, Japan, May 2017.
8. Limaye, S.S., and the Akatsuki team, Venus looks different at different wavelengths, Venera-D Modeling Workshop, Space Research Institute (IKI), Moscow, Russia, 5-7 October 2017
9. Limaye, S.S., T. Satoh, T. Horinouchi, J. Peralta and T. Imamura, Meso-scale circulations on Venus, 8th Solar System Symposium, Space Research Institute (IKI), Moscow, Russia, 9-13 October 2017.
10. Limaye, S.S., R. Mogul, A. Yamagishi, A. Ansari, D.J. Smith, G. Slowik, P. Vaishampayan, Y.J. Lee, 14th VEXAG Meeting, Applied Physics Laboratory/Johns Hopkins University, Laurel, MD, 14-16 November 2017.

6. Outreach and Communications

The Akatsuki Mission provides an unprecedented opportunity to utilize international missions for outreach and communications in the absence of any NASA missions to Venus in recent history by continuing the efforts and programs previously developed in conjunction with the European Space Agency's (ESA) Venus Express Mission's (VEX) which ended in 2014. The unusual opportunity to have an almost continuous collection of new data allows for sustained public communication and citizen scientist efforts focused on the earth's nearest and most comparable planetary neighbor within this solar system. The continued investigation of the Venusian atmosphere and its weather in particular has become of critical interest to the scientific community as well as the general public, as it provides a relatively accessible, natural planetary laboratory with the potential to greatly enhance our understanding of the earth's own atmosphere and more recently, an opportunity to explore the potential for past or present life within the Venusian clouds. Along with the successful leveraging of ongoing partnerships, programs and activities, the Akatsuki communication initiative continues our team's efforts to effectively communicate the critical scientific significance of Venus and its dynamic, potentially life supporting atmosphere.

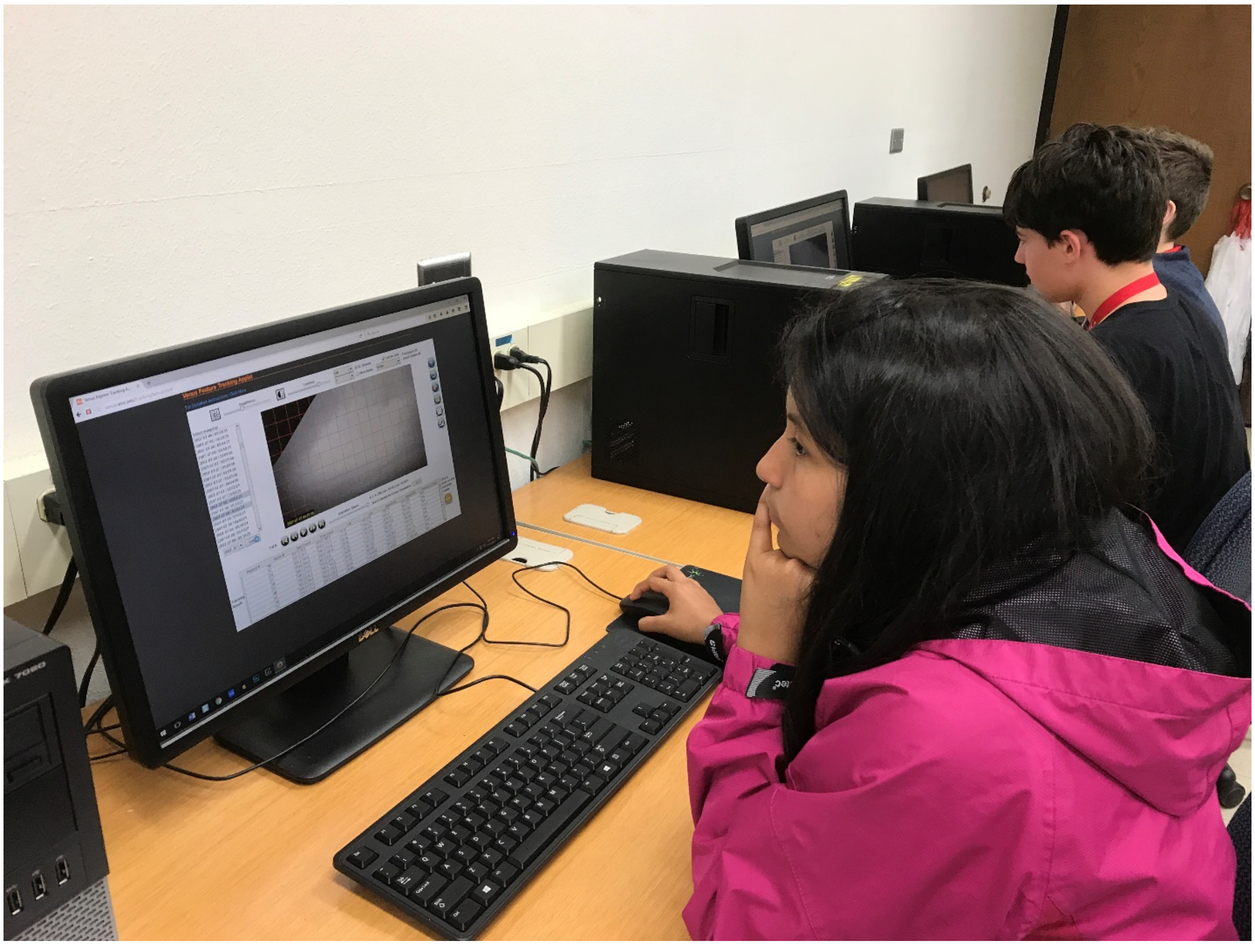
Accomplishments

In the past year, the Akatsuki communications and citizen science initiative has maintained a continuous effort to represent the research performed under this grant in a comparative planetology context to some extent. Highlights to date include, i) development and re-launch of a dedicated web presence (venus.wisc.edu) that will be updated with Akatsuki Mission news and events, ii) planning for the adaptation of an applet to enable tracking of winds on Venus using new Akatsuki data, iii) support of hands on activities to introduce Gifted and Talented Middle/ School Students (UW-Madison PACE Program) to learn about the processes of research using the Venus winds applet, and iv) Visiting Scientist presentations at schools and other presentations at special events and activities locally and internationally. These are described below.

6.1 Workshop for Students

<u>Preparatory Academic Campus Experience (PACE) - UW Madison</u>

This program gives current 5th through 8th grade students an opportunity to explore their current interests and passions with like-minded peers in a college setting. Students will spend one week taking one accelerated course designed specifically for middle school advanced learners on the UW-Madison campus. This program is designed to engage, intellectually challenge, and inspire young minds.



6.2 Visiting Scientist talks at schools

Dr. Limaye visited three schools in Poland through an on-going informal collaboration with the Regional Teacher Training Center in Skierniewice, Poland (facilitated by Mrs. A. E. Dąbrowska, Teacher consultant of Science Subjects and European Education). The Science Coordinator at this center has arranged many school visits and also conducts on-line programs for science teachers in which Dr. Limaye continues to participate. This collaboration has also been responsible for some new directions in research in the area of the unknown absorbers of incident solar radiation in the Venus clouds.

Talks given in May 2017 at the following schools:

1. Zespół Szkół im. Księdza Stanisława Konarskiego" in Skierniewice

   Colloquia Classica, May 17th, 2017 | Skierniewice, Poland

http://www.klasykskierniewice.pl/index.php/wydarzenia/334-spotkanie-colloquia-classica

Dr. Sanjay S. Limaye visited students at school "Zespół Szkół im. Księdza Stanisława Konarskiego" in Skierniewice, Poland to discuss Venus, the solar system, and space exploration.

2. Zespół Szkół nr 1, w Kole, 62-600 Koło ul. Poniatowskiego 22, Poland

Tel: (63) 26-16-771http://www.zs1kolo.szkolnastrona.pl/index.php?c=article&id=997

Host: Michał Kazmierczak, School Complex No. 1, Kolo

This was a repeat visit, the first one being during 2016.

Profesor astronomii z USA odwiedził naszą szkołę

Wyjątkowa wizyta: naszą szkołę odwiedził profesor Sanjay Limaye z Uniwersytetu Wisconsin w Stanach Zjednoczonych. Wizyta znanego astronoma związana jest z piątą rocznicą działalności szkolnego Klubu Młodych Odkrywców „Kolska Wyspa" oraz licznymi projektami, które realizuje nasza placówka.

Uczniowie szkoły i członkowie Klubu Młodych Odkrywców od lat biorą udział w ciekawych i niezwykłych projektach rozwijających ich zainteresowania, a związanych m. in. z badaniem kosmosu. Zainteresowania klubu obejmują również takie dziedziny jak: fizyka, astronomia, geografia, chemia, biologia, matematyka, mechatronika i informatyka. Warto dodać, że to właśnie w tej szkole realizowano w ramach zajęć lekcyjnych nauczanie mechatroniki z elementami robotyki, które dziś kontynuowane jest z uczniami należącymi do Klubu Młodych Odkrywców. W realizacji swoich projektów uczniowie na co dzień współpracują z Centrum Nauki Kopernik w Warszawie, ABM Space z Torunia, a nawet NASA – Amerykańską Agencją Kosmiczną.

Podczas wizyty w szkole profesor poprowadził wykład w jęz. angielskim na temat budowy planet skalistych w Układzie Słonecznym oraz przeprowadził warsztaty dla uczniów biorących udział w dwóch projektach:

1. EarthKAM – widok Ziemi z Międzynarodowej Stacji Kosmicznej przy współpracy z Sally Ride Science i NASA,

2. REMY-ESERO z mechatroniki dotyczący kierowania łazikiem marsjańskim na kraterze i wykonywania badań pomiarowych na jego powierzchni zorganizowanym przez biuro ESERO w CNK Kopernik w Warszawie oraz ABM Space z Torunia.

Podczas zajęć warsztatowych uczniowie zaprezentowali swoje osiągnięcia w budowie i programowaniu robotów, wymieniali się spostrzeżeniami oraz wysłuchali wskazówek naukowca dotyczących dalszej pracy. Była to już druga wizyta tego światowej sławy badacza kosmosu w szkole przy ul. Poniatowskiego w Kole, który spotka się z młodymi naukowcami na zaproszenie opiekuna klubu, nauczyciela fizyki i informatyki p. Michała Kazimierczaka.

Galeria

a. Szkoła Mojego Dziecka, miesięcznik dla rodziców, Gimnazjum nr 3 im. Ignacego Krasickiego, w Skierniewicach

http://www.gim3-skierniewice.pl/aktualnosci/12-aktualnosci/864-wyklady-dr-snajaya-limaye

"May 16, 2017. Our middle school hosted Dr. Sanjay Limaye of the University of Wisconsin-Madison in the United States. His research interests include solar systems with Venus, Mars, Jupiter, Saturn, Uranus, and global warming and climate change. Dr. Limaye gave lectures in English to our junior high school students. The first was about India, the country where Dr. Limaye came from. He told his students about contemporary India, society, culture and nature. The second lecture was devoted to the planet Venus and its comparison to Earth. Maybe, at some time, one of the students will be a participant in the Venus mission?

We hope this was not the last visit of Dr. Limaye at our school.

- *Agnieszka Jelonek-Krupińska", Host Teacher*

6.3 Public Lectures

Dr. Limaye was invited to give a public lecture as part of the outreach activities for the IAU Symposium on Space Weather of the Heliosphere held in Exeter, UK during 17-21 July. An audience of approximately 300 persons of all ages filled the auditorium for this lecture ("Venus – An exoplanet next door" which followed immediately after a lecture by Dr. Lucie Green on the workings of the Sun.

"Venus – an Exoplanet next door"

Tuesday, July 18, Exeter, Streatham campus, Northcott Theatre, following the lecture above – please book here or share it on Facebook.

Public lecture by Dr Sanjay S. Limaye, University of Wisconsin, Madison, USA

In 1761 Lomonosov observed the transit of Venus as it crossed the Sun's disc, making the first observed discovery about another planet – that our nearest solar system neighbor had an atmosphere. This technique has led to the discovery of thousands of planets around other stars. Nearly two hundred years later in 1962, the Mariner 2 spacecraft successfully flew past Venus and made the major discovery that the planet's surface was extremely hot. Since then Venus has been explored by atmospheric entry probes, landers, balloons and orbiters in addition to being observed by spacecraft on their way to other destinations. We have discovered that the cloud covered planet which takes longer to rotate about itself than to orbit the Sun is still shrouded in mystery. If we cannot understand our closest planetary neighbor, how can we really appreciate with confidence the mysteries of other exoplanets beyond our own solar system?

Sanjay Limaye is a planetary scientist at the Space Science and Engineering Center at the University of Wisconsin–Madison.

6.4 Planned Future Activities (December 2017 through December 2018)

Planned activities include: 1) Ongoing website updates, 2) addition of new Akatsuki data to enhance the Venus winds applet, 3) Participation in the UW-Madison PACE program for Middle School students, and 4) submission of a UW-Madison Baldwin proposal to create a research course credit opportunity for the Madison Area Technical College's STEM Center (targeting minority and low income students) using the Venus Wind Tracking applet.

References

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Appendix 1

Preprints of papers

1. Copy of "Venus Looks Different at Different Wavelengths: Morphology of the Global Day and Night Cloud Cover at Different Wavelengths from Akatsuki Cameras" submitted to Earth, Planets and Space.

2. Copy of "**Venus' Spectral Signatures and the Potential for Life in the Clouds"** submitted to Astrobiology.

Earth, Planets and Space

Venus Looks Different at Different Wavelengths: Morphology of the Global Day and Night Cloud Cover at Different Wavelengths from Akatsuki Cameras

--Manuscript Draft--

Manuscript Number:	EPSP-D-17-00201R1
Full Title:	Venus Looks Different at Different Wavelengths: Morphology of the Global Day and Night Cloud Cover at Different Wavelengths from Akatsuki Cameras
Article Type:	Full paper
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Abstract:	Since insertion into orbit around Venus on December 7, 2015, Akatsuki orbiter has returned unprecedented global images of Venus from its four imaging cameras at ultraviolet (283 and 365 nm), near infrared (1 to 2.3 μm) and at thermal infrared (8-12 μm) showing the dynamic morphology of its day and night time cloud cover nearly continuously. Past orbiting or fly-by missions to Venus did not provide such long-term global, wide spectral range or frequency of observations. The day side cloud cover imaged at the ultraviolet wavelengths shows morphologies similar to what was observed from Mariner 10, Pioneer Venus, Galileo, Venus Express and MESSENGER, but the day time images at 0.9 and 2.02 μm also reveal some interesting features which bear similarity to the ultraviolet images. The night time images at 1.74, 2.26 and 2.32 μm and at 8-12μm reveal features not seen before and show new details on the night side structure and ribbon like narrow width, long scale waves, frontal boundaries and even small vortices. Some features seen previously, such as Circum-Equatorial Belts (CEBs) and occasional brightenings at ultraviolet (seen in Venus Express observations) of the cloud cover at ultraviolet have not been seen so far. Evidence for the hemispheric vortex organization of the global circulation can be seen at all wavelengths on day and night side. The cloud morphologies provide some clues to the processes occurring in the atmosphere and are thus a key diagnostic tool when quantitative dynamical analysis is not feasible due to lack of sufficient information.
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Venus Looks Different at Different Wavelengths: Morphology of the Global Day and Night Cloud Cover at Different Wavelengths from Akatsuki Cameras

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Abstract

Since insertion into orbit around Venus on December 7, 2015, Akatsuki orbiter has returned unprecedented global images of Venus from its four imaging cameras at ultraviolet (283 and 365 nm), near infrared (0.9 to 2.3 μm) and at thermal infrared (8-12 μm) showing the dynamic morphology of its day and night time cloud cover nearly continuously. Past orbiting or fly-by missions to Venus did not provide such long-term global, wide spectral range or frequency of observations. The day side cloud cover imaged at the ultraviolet wavelengths shows morphologies similar to what was observed from Mariner 10, Pioneer Venus, Galileo, Venus Express and MESSENGER, but the day time images at 0.9 and 2.02 μm also reveal some interesting features which bear similarity to the ultraviolet images. The night time images at 1.74, 2.26 and 2.32 μm and at 8-12μm reveal features not seen before and show new details on the night side structure and ribbon like narrow width, long scale waves, frontal boundaries and even small vortices. Some features seen previously, such as Circum-Equatorial Belts (CEBs) and occasional brightenings at ultraviolet (seen in Venus Express observations) of the cloud cover at ultraviolet have not been seen so far. Evidence for the hemispheric vortex organization of the global circulation can be seen at all wavelengths on day and night side.

The cloud morphologies provide some clues to the processes occurring in the atmosphere and are thus a key diagnostic tool when quantitative dynamical analysis is not feasible due to lack of sufficient information.

Keywords

Venus Clouds, Morphology, Day-side, Night-side, Ultraviolet, Near Infrared

Akatsuki Observations

Akatsuki orbiter was originally planned to be inserted into orbit around Venus on 7 December 2010 after a successful launch on 21 May 2010. However, a malfunction during the procedure led to the spacecraft miss the orbit insertion and ended up in a ~ 205 day orbit around the Sun (Nakamura et al., 2016), changing to 199 day period by November 2011. Heroic rescue efforts by the Akatsuki team orbit insertion was finally achieved on 7 December 2015, a rare reprieve for a planetary mission. Akatsuki orbiter is providing images of Venus comparable to or better than those obtained from the Venus Express VMC instrument. Only the LIR camera images are much smaller (~ 18 pixel diameter) at apoapsis. Imaging in reflected light is performed in portions of the orbit when the phase angle is appropriate with imaging at roughly two hour intervals. Imaging of the night side of Venus is limited to portions of the orbit when the angular separation between the Sun and Venus is larger than 26.5° to avoid stray light. Also, pointing is adjusted to keep as much of the saturated day-side portion of the planet out of the field of view of IR2 and IR1 cameras as possible to minimize contamination of the data by the bright dayside portion of the planet. Additionally, data communication to the 64 m Usuda Deep Space Station near Nagano, Japan occurs daily for about eight hours when observations are not possible. The three filters with band pass centered at 0.9, 0.97 and 1.07 μm are used for imaging the surface in the CO_2 windows where the atmosphere and the clouds are largely transparent and hence do not reveal any cloud morphology, but can be useful perhaps to retrieve some of the properties.

Introduction

The cloud cover on Venus is ubiquitous, unlike on Earth and Mars. That it shows no contrast at most reflected wavelengths except ultraviolet has been known for a long time. The ultraviolet contrasts were first discovered by Quénisset in 1911 visually and recorded as drawings (Dollfus, 1975; Ross, 1927) and photographed by several observers in blue-violet in 1920s (Ross, 1927), and it was subsequently when more frequent ultraviolet images were obtained and showed variability that the images revealed clouds and not features on the surface. First spacecraft images were obtained over an eight day period during the Mariner 10 fly-by of Venus in February 1974 (Murray et al., 1974). The morphology of the cloud cover from these images and their relationship to the Y-features seen prominently in earth based images has been presented by Dollfus (1975). Pioneer Venus orbiter imaged Venus at spatial resolution of ~ 25-40 km at 370 nm using a spin scan technique but it took between 2 and 5 hours to complete one image in the eccentric orbit (Travis et al., 1979a; Travis et al., 1979b). Most of the features identified in Mariner 10 images during its short coverage were also seen in the longer duration of Pioneer Venus orbiter and the morphology was presented by Rossow et al. (Rossow et al., 1980). Venera 9 and 10 orbiters also obtained 17 images covering a limited portion of the sun-lit planet during 26 October – 25 December 1975 using the motion of the orbiters with a 512 element linear photometer array with 30° wide field of view at violet and ultraviolet wavelengths (Keldysh, 1977). Pioneer Venus orbiter (PVO) also obtained lower resolution images (365 nm global images with a few limb images at 365 and 690 nm) and polarization data (~ 100 km per pixel) in reflected sunlight at four wavelengths (270, 365, 550 and 935 nm) which showed morphology to be similar at 270 and 365 nm in unpolarized light, but also showed similar features in polarization data at the two longer wavelengths (Limaye, 1984). The Orbiter Infrared Radiometer (OIR), a 6 filter instrument on PVO also yielded thermal infrared views of the northern hemisphere cloud tops at 10.6 -12.6 μm for about two months (Apt et al., 1980; Taylor, 1980). Galileo orbiter took images of Venus (Belton et al., 1991) over a very short period (2.5 days) in February 1990 at two different wavelengths in reflected light (420 and 990 nm effective wavelengths) which showed morphologies to be similar to the Mariner 10 and Pioneer Venus observations (Belton et al., 1992), but at near infrared wavelengths (1-3 μm) showed surprising detail on the night side (Carlson et al., 1991). The Venus Monitoring Camera (VMC) (Markiewicz et al., 2007) on Venus Express orbiter (Svedhem et al., 2007) imaged Venus at 365, 513, 950 and 1010 nm and the mapping channel of the Visible Infrared Thermal Imaging Spectrometer (VIRTIS) imaged Venus between 0.28 – 5.1 μm during 15 April 2006 – 27 November 2014 and predominantly provided a polar view of the Venus cloud cover at ~ 25-45 km per pixel size and detailed views of the equatorial and northern latitudes at a spatial scale of as high as 1-2 km per pixel. The VIRTIS-M used separate detectors of the short wave and infrared regions. The shortwave data are still being fully calibrated to remove instrumental effects. The near infrared data showed new details of the polar regions of Venus not readily accessible to Akatsuki and imaged primarily the southern hemisphere between 200 nm – 5 µm wavelgnths at moderate spectral resolution. At tne near infrared (NIR) wavelengths these data showed the morphologies of features formed by CO_2 non-LTE emmissions (Garcia et al., 2009) in the upper atmosphere, details of the nightside upper oxygen airglow (Soret et al., 2014). The NIR data also showed nightside upper clouds (Peralta et al., 2017) and lower clouds (Hueso et al., 2012). VIRTIS also revealed the intricacies of the inner region of the (southern) hemispheric vortex circulation (Garate-Lopez et al., 2015; Luz et al., 2011) which were not seen in the ultraviolet views that revealed the vortex from space-time composites of Mariner 10 day-side images (Suomi & Limaye, 1978).

In Venus Express observations the 365 nm morphologies seen showed the same basic features detected from previous missions, but showed some new aspects of the cloud cover, particularly because of its polar vantage point ((Markiewicz et al., 2014; Titov et al., 2012). The VIRTIS experiment (Piccioni et al., 2007a) of Venus Express imaged Venus from 0.3 to 4.3 µm and showed the intricacies of the inner region of the (southern) hemispheric vortex circulation (Limaye et al., 2009; Suomi & Limaye, 1978) about the poles of Venus in each hemisphere. MESSENGER spacecraft imaged Venus from its wide and narrow angle cameras in June 2007 and provided more than two hundred images of Venus in 10 nm spectral bands (wide angle only) at a twelve wavelengths over about two days.

It is useful to note that on Earth cloud morphologies look very similar from blue to thermal infrared wavelengths (Figure 1), unlike on Venus (Figure 2). Images taken from Himawari satellite at sixteen different wavelengths between 410 nm and 15 µm are shown in Figure 1 while similar wavelength coverage for Venus is shown in Figure 2 from recent missions. Unlike the Earth images which are concurrent, we have only limited concurrent coverage over the same spectral range from MESSENGER fly-by data and is supplemented by Galileo and Akatsuki for illustrative purpose. The MESSENGER images are taken from the MDIS Wide Angle camera (Hawkins et al., 2009; Robinson et al., 2007) with narrow band filters (10 nm) comparable to the band pass of the Akatsuki images at 283and 365 nm (Table 1).

The difference between the wavelength similarity for Earth and for Venus is striking and suggestive of the compositional differences between Earth and Venus clouds. Venus clouds are complex as we have discovered. Although the ultraviolet contrasts were first discovered more than a century ago (Dollfus, 1975), and that the clouds are composed of sulfuric acid for nearly five decades (Hansen & Hovenier, 1974) we still do not know what substance(s) are responsible for them except that sulfur dioxide gas is one of them and there is at least another absorber which is as yet unknown (Travis, 1975). Morphologies provide a good diagnostic tool for relating the atmospheric processes involved with the sources and sinks of the aerosols, condensates and trace gases that are involved. There are more than one hundred and forty chemical reactions involving sulfur in the atmosphere of Venus and may more involving other elements. Venera and VeGa landers, four Pioneer Venus probes and two VeGa balloons have sampled the clouds below 62 km and obtained useful measurements, but these are proving to be insufficient in understanding the clouds of Venus.

Against this background, the observations from Akatsuki cameras are providing high quality global images at wavelengths where Venus over an extended period enabling a study of the global morphologies and shedding new light on the clouds of Venus. Akatsuki orbiter's cameras are now imaging Venus at thirteen wavelengths from 283 nm to 10μm. These images provide global views of the day and night side of Venus at spatial scales from ~ 70 km to as high as 0.2 km per pixel. Concerning cloud morphology, Akatsuki provides the best global views of Venus at several wavelengths for the first time – 283, 900, 2020 nm on the day side and at 0.97, 1.01, 1.74, 2.26 and 2.32μm on the night side while the LIR camera provides day and night side views of Venus at the thermal wavelengths.

The morphological investigation at the multiple wavelengths enabled by Akatsuki cameras presented here provides new constraints on the clouds – both ultraviolet absorbers responsible for day side patterns and local variations in cloud opacity for the night side patterns. We describe here the morphology of the day side cloud cover (283, 365, 900 and 2020 nm) for the first time and also the night time morphology from 1.74, 2.26 and 2.32 μm images that shows amazing detail not previously seen in either the ground based observations or from the VIRTIS/Venus Express coverage.

Akatsuki Multispectral Images of Venus: Cameras on board

There are five cameras on Akatsuki to image Venus at UV to thermal infrared – UVI [Yamazaki et al. submitted to EPS, same issue], IR1 (Iwagami, 2011), IR2 (Satoh et al., 2016), and LIR (Fukuhara et al., 2011) wavelengths and Lightning and Airglow Camera (LAC) which does not produce an image (Takahashi et al., 2008) which is operated when the night side of Venus is visible to Akatsuki to detect lightening and airglow. Table 1 provides the characteristics of the four imaging cameras. The 1.65 μm filter in the IR2 camera was used for zodiacal imaging during cruise and is not used to image Venus and hence is not listed in this table. The focal lengths are nominal values and have been updated from star fields during the mission for IR2 camera, and updates are expected for the other cameras. During the long interval between the first attempt in December 2010 and the successful one in December 2015, Akatsuki came much closer to the Sun than anticipated with 11 perihelion passages. Thus the camera performance was affected somewhat, particularly for the IR1 camera, requiring new procedures for calibration of the data.

Table 1. Characteristics of cameras on Akatsuki Orbiter

Camera	Channel Name	Band Center (μm)	Bandwidth (micron)	Transmittance	Pixel Size (mm)	# Lines	# Samples	Focal Length (mm)	Day/Night
IR1	090d	0.900	0.00910	0.0027	0.017	1024	1024	84.2	Day
	090n	0.898	0.02890	0.74	0.017	1024	1024	84.2	Night
	097	0.969	0.03860	0.78	0.017	1024	1024	84.2	Night
	101	1.009	0.03910	0.75	0.017	1024	1024	84.2	Night
IR2	174	1.735	0.041	0.85	0.017	1024	1024	85.41	Night
	226	2.26	0.052	0.67	0.017	1024	1024	85.44	Night
	232	2.32	0.036	0.67	0.017	1024	1024	85.41	Night
	202	2.02	0.039	0.06	0.017	1024	1024	85.50	Day
	165	1.65	0.283	0.93	0.034	520	520	85.35	-
UVI	283	0.283	0.014	0.280	0.013	1024	1024	63.3	Day
	365	0.365	0.014	0.509	0.013	1024	1024	63.3	Day
LIR		10.00	4.00	-	0.037	328	248	42.2	Day and Night

Generally, when Akatsuki orbiter predominantly views the night hemisphere of Venus from its position in its ~ 11-day orbit around Venus, the UVI camera is not used, and only IR1 (IR1_9N and IR1_101 filters) and IR2 (IR2_174, IR2_226 and IR2_232 filters) cameras image the night side of Venus in selected filters. The 1.65 μm filter of IR2 is for zodiacal light studies and was used only during cruise. The LIR camera images Venus throughout the orbit – day and night as it senses radiation emitted to space by the planet from the cloud tops. Dayside images are taken from the UVI camera at 283 and 365 nm wavelengths as well as at 0.9, 1.01 (IR1) and 2.02 μm (IR2) wavelengths. Instrumental constraints prevent concurrent images from different filters from the same camera but the time interval is relatively short (about 214 seconds for UVI) which provides near simultaneous imaging at different wavelengths except at close approach to Venus.

Temporal Coverage

Only four hours after Venus Orbit Insertion (VOI), the IR1, UVI and LIR cameras took Venus images. Only IR2 waited to be cooled down for 10 days and took "first light" images after a long hibernation period also in December 2015, but the first Venus images from IR2 were obtained in January 2016. Akatsuki began its systematic data collection in April 2016 from its near equatorial orbit with periapsis altitude of ~ 1000 km and a 10.5-day period and an eccentricity of about 0.92 (Figure 3). Routine imaging from all four cameras began on 1 April 2016 and has continued on every orbit. In November 2016 a technical problem prevented imaging from IR1 and IR2 cameras which share some electronics, and currently those two cameras are not returning any data. The cadence of most of the images from UVI, IR1 and IR2 cameras is two hours, but some have been acquired one hour apart for better temporal sampling. Generally, UVI camera makes three exposures for one "image" and a median filter is applied to reduce the dark noise and this procedure takes 210 seconds. But at close approach to Venus the median filter is not applied and images can be acquired quicker (150 seconds apart). The LIR camera can image Venus every four seconds. The total number of images returned from Akatsuki is thus somewhat less than the number of images returned from VMC, but the overall quality and image resolution are better, and provide global views of the planet than only a south polar view from the majority of the images.

Day Side Morphology

283 nm, 365 nm (UVI) Images

A representative sampling of images taken through the 283 and 365 nm filters are shown in Figure 4. At first impression the cloud forms seen at these two wavelengths are very similar as the clouds absorb some of the incident ultraviolet radiation, however some differences in the relative brightness and contrasts are seen. In general, the contrast of the images is somewhat lower at 283 nm than at 365 nm. This is somewhat unexpected as SO_2 is expected to absorb some of the radiation at this wavelength, along with another absorber (Esposito, 1980; Esposito et al., 1983). The intensity data acquired from Pioneer Venus Orbiter Cloud Photopolarimeter showed somewhat larger contrasts at 270 nm compared to 365 nm at 0 - 90° phase angle , at least when contrast was defined in terms of absolute deviation from the intensity expected from a Minnaert law behavior. Despite the somewhat lower contrast, 283 nm images show generally the same morphology as 365 nm images, but the smaller scale details are muted or absent.

The Akatsuki images show features seen before – discrete smaller scale features at low latitudes, bright spiraling streaks and bands at mid-latitude, bow like features near the sub-solar point and the Y-like feature in different shapes. As before, the contrasts are lower near terminators. A more detailed study of the Y-feature and a study of the evolution of morphology and contrasts at 283 and 365 nm data are underway and will be reported by others in the near future. Scattering properties of the clouds at 283 and 365 nm as deduced from Akatsuki data have been reported recently (Lee et al., 2017) which confirm that SO2 and the unknown UV absorber are necessary factors to explain the decreasing trend of the observed relative albedo at phase angles larger than 10°.

Day side Images at 900 nm (IR1)

Images taken through the 0.9d filter on the day side of Venus are shown in Figure 5. As expected from previous observations (Coffeen et al., 1971), the full disk image of Venus shows little detail as the contrast is very low. Low to medium spatial resolution full disk images show somewhat less bright polar regions compared to the ultraviolet, showing similar darkening as seen at 2.02 µm. Digital filtering brings out subtle contrasts on very small scales (~ 10-20 km) at 0.9 and 2.02 µm. Some examples are shown in Figure 5 – images B,D, and F are high pass filtered images. Images C and D are mapped at 0.025° per pixel in latitude and longitude to present the same scale since Image E was obtained at a range of 16,467 km and “F” at 17,458 km (3.38 and 3.52 km/pixel respectively) and the two images are only about 12 minutes apart, showing rapid changes in the small scale contrasts. Both E and F images show the equatorial region and span an area approximately 400 x 400 km. On this small scale the origination of the bright streaks at 365 nm is almost orthogonal to the latitude circles, unlike the general pattern of streaks seen over larger scales which are inclined at a smaller angle, giving the impression that they are streak lines (Smith & Gierasch, 1996).

Similar to the variable correlation between the 283 and 365 nm brightness distribution over concurrent images from Akatsuki UVI camera, the correlation between the wavelengths covered by Galileo and MESSENGER images was also found to vary. During the Galileo flyby there seemed to be an "anticorrelation" in brightness between the violet and near-infrared images (Belton et al., 1991), but this anticorrelation was not apparent during the MESSENGER fly-by (Peralta et al. 2017a). Analysis of the Akstsuki data correlation between short and long wavelengths is underway and will be reported later.

Day side Images at 2.02 µm

Full disk day side 2.02 µm images from the IR2 camera are shown in Figure 6. The polar regions (> 60º latitude), appear noticeably darker at this wavelength close to the equatorial boundary of the “cold collar” seen in the thermal data. At this wavelength some of the radiation reflected from the clouds is absorbed by CO2, the dominant constituent of the Venus atmosphere. The darker regions thus suggest lower cloud tops, which would be consistent with the lower cloud tops inferred from VIRTIS data at 1.74 µm using the same approach by Ignatiev et al. (2009). The equatorial and mid-latitude regions show faint details somewhat similar to those seen at ultraviolet wavelengths. The classic Y-shaped feature can be discrned often. There also appears to be some phase angle dependence as very few details are visible at phase angles > 120º.

Morphology at Smaller scales (~2 to ~5 km/pixel)

The structures on smaller scale are somewhat different from the patterns seen on a global scale. VMC images showed fine scale gravity waves in northern latitudes (Piccialli et al., 2014) which were not seen previously and have not yet been seen in Akatsuki images at any wavelength. Images at ~2 to ~5 km/pixel scale are generally acquired by Akatsuki cameras at low latitudes and show somewhat surprising structures. Figures 7a shows a selection of views from UVI and IR1 cameras. Only contrast filtered versions are shown as the calibrated images do not show any discernable details. Figure 7b shows 2.02 images in both calibrated and contrast filtered versions. In general the contrasts are even lower on such small spatial scales and are brought out only after some filtering. The contrast filtered versions were created by dividing the root mean square deviation over a box (9x9 or 11x11) centered over a pixel by the average of the pixels within the box. Images A and B show thin, string like features of variable lengths, curvature and inclinations to latitude circles. Image C however is surprisingly devoid of such features but shows a bright region core surrounded by a dark ring like the classic signature of the glory feature which has been seen in the Venus Monitoring Camera at 365, 550, 950 and 1050 nm (Markiewicz et al., 2014), but the geometry is not consistent with the backscatter angle and the feature is believed to be due to low frequency bias and cross-talk between the four qudrants of the IR2 readout electronics (Satoh et al, this issue).

Near simultaneous global images of Venus at 283, 365, 900 and 2020 nm on three separate days (almost one orbit apart) are shown in Figure 8. The near infrared images are shown in filtered versions to bring out the contrasts. The transition between lower and higher brightness matches well at 283 and 2.02μm while the transition occurs at a slightly lower latitude at 365 nm. Polewarrd of this quasi linear streaks can be seen at all four wavelengths which are equivalent to the spiral arms of the vortex over the pole. The two longer wavelengths should probe the deeper levels of the clouds compared to the UV wavelengths, but at 2.02 μm CO_2 absorption also plays a role. Thus when similar features or structures are seen at all four wavelengths, the features extend from near the top to at least a scale height deeper. When the features are not similar, the cloud cover is likely layered.

Variations in Cloud Properties: Contemporaneous views at 283, 365 nm, 1.02 μm and 2.02 μm

Figure 9 shows images obtained close together in time and at spatial scale of about 6 km per pixel at 283, 365nm and 2.02 μm in the top row mapped in latitude and longitude. The lower column shows a color composite with 283 nm shown in blue, 2.02 μm in red and 365 nm image in green. Subtle color variations over the overlapping area from yellow to purple or brown are suggestive of differences in the distribution of sub-micron haze (~ 0.2 μm radius), the cloud particles (~ 1.2 μm radius), larger particles and possible differential CO_2 amounts over the “cloud-tops”. More bluish and/or greenish indicate less abundances of UV absorbers, while reddish indicates higher cloud top level than that over rest area owing to less CO_2 absorption above the cloud top altitude at the CO_2 band (2.02 um). Figure 9 shows yellowish in the 10° S -10° N latitude, implying the area has less unknown UV absorber and the cloud top level is higher than surrounding region.

Night Side Morphology

1.74, 2.26 and 2.32 μm Images from IR2 Camera

Figure 10 shows a selection of night time images taken from the IR2 camera at 1.74, 2.26 and 2.32 μm which reveal a very different morphology than that seen on the day side. Also included are two sample images (U and X) from the NASA Infrared Telescope Facility (IRTF) located at Mauna Kea, Hawaii. These two images are part of a ground based campaign to collect supplemental images in support of Akatsuki mission. Although the NIMS (Galileo) and VIRTIS (Venus Express) instruments also provided images at these wavelengths, the temporal coverage was too short due to the fly-by nature of Galileo observations and VIRTIS was not able to image the low latitudes or provide global views of the planet from an equatorial perspective due to the elongated, polar orbit of Venus Express.

Thus Akatsuki images reveal for the first time the complex and puzzling morphology of the cloud cover on the night side. At the wavelengths near 2 μm, the features seen in the images have been interpreted as being seen as back-lit silhouettes illuminated by the radiation emitted by the increasingly warming atmosphere below the clouds towards the surface and the surface itself. While differences in either the amount of UV absorbers or cloud altitudes as on the dayside lead to changes in the day side appearance of Venus, the varying near infrared opacity of the clouds is responsible for the features seen at near infrared wavelengths seen in previous ground based, Galileo/NIMS and VEX/VIRTIS images. However, the features seen in the Akatsuki IR2 images suggest that dynamics may play a significant role in the night side morphology. For example, images G, H and I of Figure 10 at 1.74, 2.26 and 2.32 μm show a long linear dark streak (low intensity) at some angle to the latitude circles as well as a very bright (high intensity). Different processes may be producing a very high linear opacity feature in the case of the dark streak and a very localized “hole” in the overlying cloud to let the near infrared radiation leak through from the lower atmosphere to space.

Sharp Boundaries or Frontal Zones?

Some night side IR2 images show a sharp linear boundary running north-south across which the intensity varies noticeably. What is remarkable is the sharpness of the boundary with changing orientation. Origins of such sharp opacity regions are not easy to explain dynamically without invoking “different air masses” as was suggested to explain the VeGa balloon dynamical results (Blamont et al., 1986), but then the challenge is explaining the origins of different air masses.

Another example is illustrated by images J, K L as well as M, N and O of Figure 10 in which a very sharp, irregular boundary with a very sharp right angle boundary is seen at all three wavelengths between high and low intensity. Figure 11a shows another example with very striking intensity boundary in a 2.26 μm image, reminiscent of a front. This boundary remains more or less intact for some time before dissipating, much as the expanding plume from a volcanic eruption or a dust storm front. On Earth sharp boundaries are also seen in water vapor channel images are seen often (Figure 11b) revealing different mid-low tropospheric water vapor abundances. The right angled between dry (dark) and moist (gray) seen in Figure 11b southeast of Japan is similar to the feature in images M, N and O in Figure 10. Trace gases such as water vapor, HF, CO and COS are optically active in the 2.3 μm region and can be responsible for such discontinuities but the cause for such demarkation in the species abubdances are unclear, but volcanic eruptions can be one. Since such boundaries are not apparent in the UVI images, the differences in the abundances are restricted to middle and lower part of the cloud, perhaps due to the incresing stability of the atmosphere. Magurno et al. (2017) have examined VIRTIS data between 25-55° latitude to explore cloud particle properties and trace species and find that sulfuric acid concentrating making up the cloud particles may be varying vertically and that near 2.3 µm, water vapor, CO and COS affect the observed intensities (they did not include CS_2). Regional dynamics must therefore be responsible to create the observed sharp boundaries which leads to the question of the sources and sinks of the trace species.

Images S and T of Figure 10 also show a similarly sharp boundary, but in this case the low intensity region is shaped like a dark streak. Ground based IRTF images (U and X) also show large contrasts in the intensities in the K-continuum filter. Once again, it is not easy to explain the causes of such features, except to say that somehow the local dynamics must play a role in affecting the distribution of aerosols at the levels involved. These features serve as a caution against basing interpretations of the observations on the VIRA model globally as the local deviations are clearly significant. At this point it is premature to assess the impact of these opacity variations on the heat deposition in the atmosphere which is believed to be driving the superrotation of the deep atmosphere of Venus.

At high spatial resolution all three wavelengths show bright,thin, sinuous wispy streaks like features against a darker (lower intensity) background (Images P, Q and R). Such features have not been detected on the day side at any wavelength in the images obtained so far. Often these features are seen to criss-cross, suggesting perhaps some altitude difference analolous to terrestrial cirrus, but we have little additional data or information at this time. Regardless, their presence is undoubtedly due so some cloud particle formation process in the middle of the cloud layer which is affected by trace species, condensation nuclei and temperature and cloud forming substances such as sulfuric acid which is believed to form in the upper portion of the cloud layer, but not photochemistry.

The Y-Feature absent on night side?

The Y-feature and its numerous shape varieties seen in the ultraviolet images of Venus is conspicuously missing in the night time images taken at 1.74, 2.26 and 2.32μm. This suggests some vertical limits on the dynamical processes that produce this recurring feature, e.g. that it is the result of the distortion of an equatorial wave as it propagtes within a latidudinal varying zonal wind differing from solid body rotation (Peralta et al., 2015). To some extent, the appearance or the perception of the Y-shaped features appears to be related to the relative spatial resolution of the images. It is far easier to this feature in lower spatial resolution images than in high resolution images. This is probably due to the scale dependence of the contrasts seen in the cloud cover of Venus. The contrasts on small spatial scales (<< 100 km) is very low compared to the contrasts seen at larges scales (>> 100 km), as can be seen from images shown in Figures 4 and 5.

Small scale vortices

Small scale, local circulations, including vortices are also seen in a few of the images for the first time on Venus (D,E,F in Figure 10) which resemble “mushroom” like features seen in water vapor images of Earth from synchronous weather satellites (Houghton & Suomi, 1978). These features are being presented by Limaye et al. (2017). Origin of such small scale circulations was not expected due to the low rotation rate which places Venus in a “symmetric” circulation regime rather than a planetary wave regime as was discovered by R. Hide (Hide, 1953) and D. Fultz from dish pan or rotating annulus experiments to simulate atmospheric circulations many decades ago and analyzed extensively since then (Read, 2011; Sugata & Yoden, 1993).

Ribbons or narrow width waves

Small scale waves along a sharp boundary parallel to latitude circles have been seen in 2.32 μm images at low latitudes (~ 15º S latitude) from Akatsuki’s IR2 camera, that resembles sharp boundary between the low to mid latitude clouds and the bright band seen at 365 nm in most Venus images situated typically between 45-50º latitudes in both hemispheres (Rossow et al., 1980; Suomi & Limaye, 1978; Titov et al., 2012). Figure 12 shows an example of an 2.26 μm image in perspective view from IR2 camera (left) and in a latitude-longitude view (right). The wavelike boundary is at about -17.3° latitude. The larger intensities at higher latitudes suggest thinner (lower opacity) overlying clouds. VIRTIS observations indicated only lower cloud tops in polar regions (Ignatiev et al., 2009).

High Resolution Detail on the Nightside

Figure 13 shows a color composite of co-located 1.74 µm (red), 2.26 µm (green) and 2.32 µm (blue) images obtained from the IR2 camera at a spatial scale of ~ 11 km/pixel. All three images are shown as latitude –longitude maps with 0.1° / pixel scale. Color differences reveal subtle differences in opacity of the Venus clouds at the three wavelengths in this color composite. Thus white features have similar opacity values and different colors indicate higher or lower values of opacity. Thus areas that appear yellowish in the overlap region should indicate somewhat higher opacity at 2.32 µm compared to the other two wavelengths, and the reverse in areas where the features appear somewhat bluish. These differences appear consistent with influences of CO contribution (2.32 µm, (Tsang et al., 2009), H_2SO_4 absorption (1.74 vs. 2.2 µm (Barstow et al., 2012)), and cloud particle size (1.74 vs 2.3 µm (Wilson et al., 2008)) have been identified from Venus Express data. It seems that the compositional differences do not appear to be due to local time differences.

Thermal Infrared: Cloud Top Brightness Temperature Morphology from LIR

Pioneer Venus OIR experiment provided the first spacecraft observations of Venus at the thermal wavelengths where the emission from its cloud tops can be sensed (Taylor et al., 1980) but these were limited to northern polar regions. Akatsuki LIR camera provides the first global views of the brightness temperature distribution over the cloud cover continuously. Figure 14 shows two sample images. One of the first major discoveries was a bright band (Image A in Figure 14) aligned almost north-south with a slight curvature which has been interpreted as a standing gravity wave triggered by surface topography (Fukuhara et al., 2017). Such waves have been seen often in Akatsuki data and it has been observed that they last for a few days before dissipating. Further, these waves occur only near the evening temperature with temperature contrast of about 5-6 K with the bright and dark portions corresponding to about 230 and 225 K respectively. Surprisingly, the signature of these standing waves can also be detected at 283 nm (Fukuhara et al., 2017), and have been detected at 365 nm also.

These waves were also seen in the 986 nm images of Venus from the Galileo Solid State Imager (SSI), but were not identified as such and was described as a north south brightness discontinuity but moving with the ambient wind by Belton et al. (1991).

Except for the presence of such standing waves, the cloud cover shows very small brightness temperatures over most of the planet (Image B in Figure 14), less than 2K. Only at polar latitudes is any brightness temperature variation seen. The "cold collar" can be often identified as a darker ring surrounding the warm core region of the vortex over the pole which appears bright due to emissions from the deeper atmosphere.

What remains a mystery is that the brightness temperature contrasts related to the standing wave are much larger than any temperature contrasts between bright and dark ultraviolet features, even though a very large fraction of the absorbed solar energy is taking place at ultraviolet wavelengths. Thus the question that arises is whether the standing wave brightness temperature contrast is due to vertical altitude differences since the ambient temperature decreases with altitudes near 65 km altitude at about 6K.km^{-1} or more rapidly.

Global Organization of the Cloud Cover - Vortex situated over the poles

One morphological feature that spans both day and night cloud cover of Venus is the hemispheric global vortices in each hemisphere rotating asymmetrically about each pole. First discovered from Mariner 10 images taken in February 1974 (Suomi & Limaye, 1978), the vortex organization of the cloud level circulation has been seen in Pioneer Venus (Limaye, 1985), Galileo (Peralta et al., 2007), and Venus Express (Limaye et al., 2009) data and hence now can be assumed to be a quasi-permanent state of the global circulation. The VIRTIS experiment (Piccioni et al., 2007b) with its wide spectral coverage from UV to NIR was able to capture the complete day and night portions of the southern vortex. Akatsuki's near equatorial orbit does not provide an over the pole view of Venus, and thus the complete vortex in any day or night side filter cannot be seen and can be seen only as a space-time composite. Figure 15 presents a view of the vortex organization as obtained from Akatsuki observations at three wavelengths. An example is shown in Figure 14a by using only two 365 nm images separated by two days with one image rotated by 180 degrees to show the correspondence of the spiral features. The central oval shaped core region which is somewhat depressed in altitude can be seen. Figure 15b shows the finer structure in the north and south hemisphere vortices from 2.02 µm observations. The fine scale structure could be due to variations in cloud altitudes if the absorption from CO_2 is considered. This is consistent with the warmer brightness temperatures from the LIR data shown in Figure 15c.

Muto and Imamura (2017); (Piccioni et al., 2007b) discuss the structure of the oval shaped core region of this vortex as observed from Venus Express VMC ultraviolet images. The thermal infrared also shows the core region is warmer and also exhibits the vortex morphology (Figure 15 b). Images taken through 2 µm filters from IR2 suggest that the vortex structure persists in the middle cloud layer seen on the night side, consistent with the VIRTIS observations,

Summary

Akatsuki data at near infrared wavelengths provide new information about the global cloud morphology on the day and night side in reflected and transmitted radiation. At ultraviolet wavelengths the new observations reveal same morphology as seen from previous missions. The day side longer wavelength images show morphologies somewhat resembling what is observed at shorter wavelengths but the details are different at the longer wavelengths, confirming the impression from the very limited images obtained during the second fly-by past Venus by the MESSENGER spacecraft on its way to Mercury. On the night side Akatsuki observations from the IR2 camera reveal new aspects of the cloud structure not seen in VIRTIS images – small scale vortices, waves. Surprisingly many wispy or string like features like cirrus clouds on Earth are also seen on the night side at low and mid latitudes which correspond to low opacity regions indicating higher radiances from the atmosphere due to warmer temperatures. How such features develop is a mystery.

What is puzzling is the impression from the motions of the VeGa balloons (Sagdeev et al., 1990) with the morphologies seen in the 2 µm band images – the VeGa balloons moved fairly smoothly horizontally about 6.5° away from the equator in the north and south hemispheres over most of their 48 hour trajectory, yet the images show a rather chaotic, dynamical situation. VeGa balloons, floating near 54 km altitude did experience some large vertical accelerations at times, some were correlated with topography. The standing gravity waves seen in LIR and UVI (283 nm) images are absent in the IR2 day side images (2.02 µm) or on the night side. At the thermal wavelengths standing waves and core region of the vortices situated over the Northern and Southern poles are the prominent features seen. Global brightness temperature contrasts are low (< ~ 5K). Analysis of the Akatsuki data from all cameras is continuing and these and future investigations should give us a better idea of the variety of different processes occurring in the atmosphere of Venus on both the day and night sides.

- Venus cloud cover appears different at different wavelengths on day side and night side compared to global cloud cover on Earth.
- Differences due to different cloud forming processes appear to be active on Venus resulting in different cloud particle constituents and responding to the temperature and pressure conditions and trace gases.
- It is not well understood why the contrasts peak at 365 nm on the day side and near 2.3 µm on the night side. Photochemistry, ambient temperatures, dynamics may all be responsible in the appearance of Venus at these wavelengths in particular.
- Absorbers of incident sunlight at $\lambda < 600$ nm include SO2, CS_2, COS which have been detected in the atmosphere of Venus and some others whose nature could be organic (Limaye et al., 2017) cannot be ruled out
- There is a clear boundary in the morphology patterns at mid latitudes at all wavelengths except at thermal infrared (8-12 µm) where the boundary is between 60-70° latitude.
- Regional dynamics must be involved in creating variations in trace gas abundances which must control the cloud opacity and reflectivity variations. But how these variations come about cannot be determined due to any information about their sources as most trace species are affected by photochemistry. The differences in the day and night and the reaction rates of the numerous chemical reactions possible in the cloud layer are somehow

responsible, but the spatial variations remain a puzzle.

Availability of data and materials

Akatsuki data will be available from the Akatsuki Project as well as NASA’s Planetary Data System in summer 2017.

Competing interests

There are no financial and non-financial competing interests.

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Authors' contributions

Drs. Watanabe, Yamazaki, Satoh, Iwagami, Taguchi and Fukuhara have been responsible for camera development, calibration and observations while Prof. Nakamura has been shepherding the Akatsuki mission and operations. Dr. Sato, Yamada, Suzuki, Hirata, Sugiyama and Ando have been involved in instrument calibration, spacecraft operations. Dr. Abe has guided the technical aspects of Akatsuki Project. Prof. Yamada contributed to Venus atmsospheric dynamics. Dr. Yamamoto, Ohtsuki, Sugiyama, Suzuki, Naru and Takagi have been involved in instrument calibration and operations. Drs. Lee and Peralta contributed to the interpretation of the data. Dr. Murakami has been responsible for pipe-line data processing operations. Dr. Nishii and Hirose have been leading spacecraft operations and trajectory. Dr. Hashimoto and Murakami are overseeing systematic data processing. Dr. Young has been collecting Venus night side imaging data from IRTF in support of Akatsuki mission. Dr. Ocampo has played a key role in the NASA-ISAS/JAXA collaboration for Akatsuki mission and overseeing the Participating Scientist Program.

Declarations

Ethics approval and consent to participate

Not applicable.

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Authors' information

SSL has been studying Venus with data from Mariner 10, Pioneer Venus and Venus Express missions prior to Akatsuki. Drs. Satoh, Iwagami have been studying Venus with ground based observations as well as spacecraft for a long time. Drs. Lee and Peralta have experience with Venus Express and ground based observations of Venus. Other co-authors have been responsible for instrument calibration, observation planning, ground processing and spacecraft operations.

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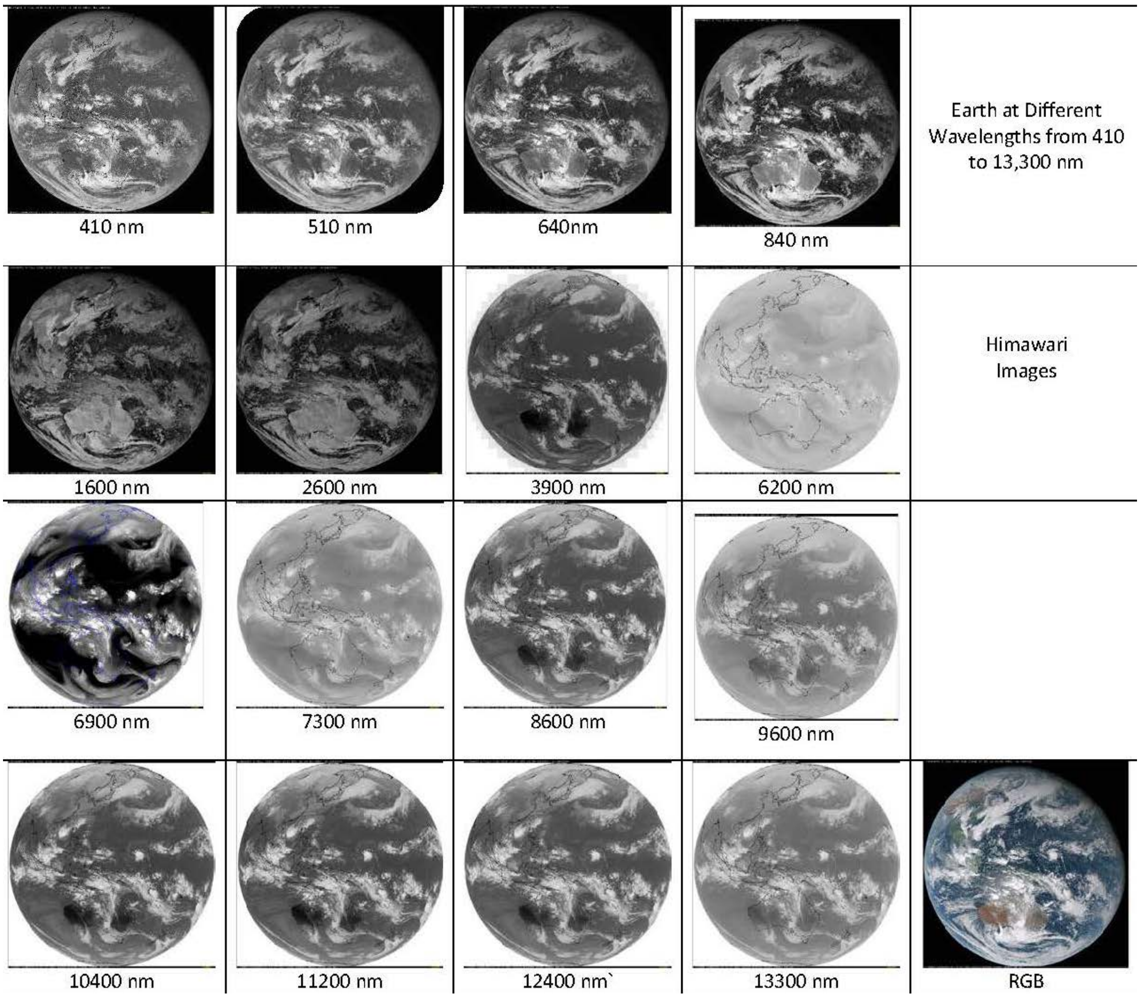


Figure 1. An example of Earth clouds imaged by Himawari weather satellite (27 December 2016, 04:00 UT) in geosynchronous orbit at sixteen different wavelengths. The cloud features show a great deal of similarity from 410 nm to 13.3 µm.

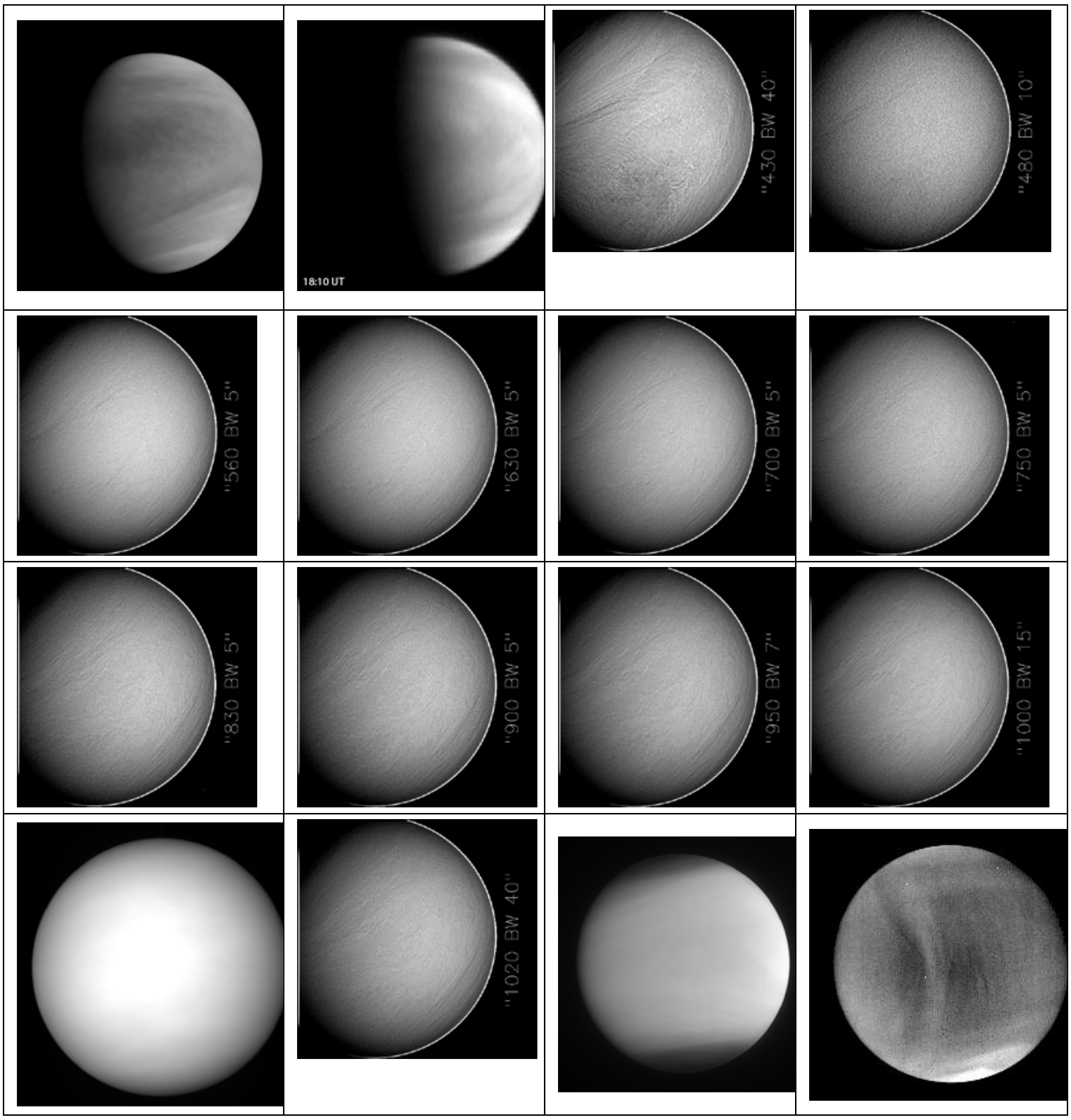


Figure 2. Venus at different wavelengths imaged by Akatsuki and MESSENGER cameras. Top row – (left to right) 283 nm, 365 nm (UVI Akatsuki), 430 nm, and 480 nm (MESSENGER –MDIS/WA). Second row – 560, 630, 700 and 750 nm (MDIS-WA). Third row- 830, 900, 950 and 1000 nm (MDIS-WA). Bottom row – 900 nm (IR1) 1020 nm (MDIS-WA), 2020 nm (IR2) and 10-14 µm (LIR). All MESSENGER images have been high pass filtered to bring out the very low contrast features.

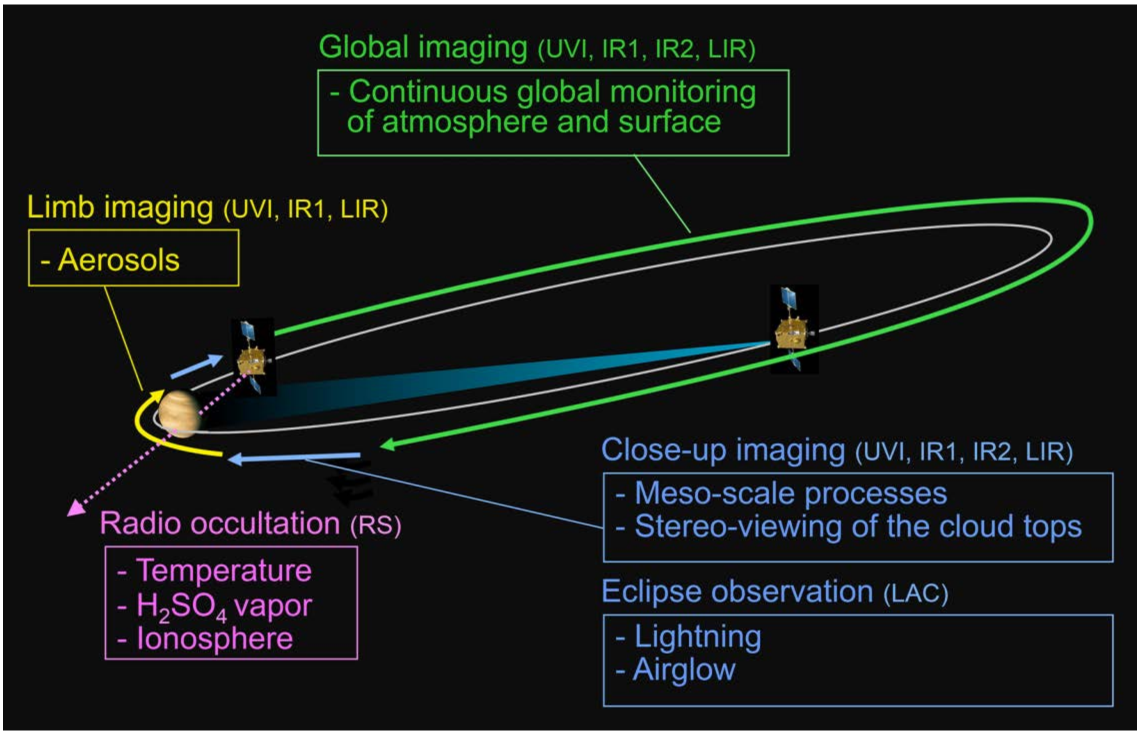
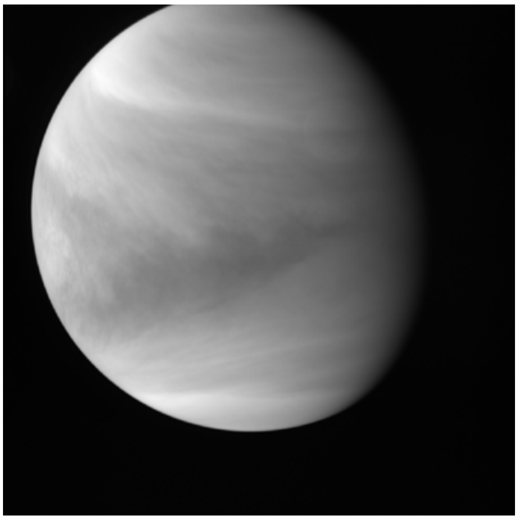
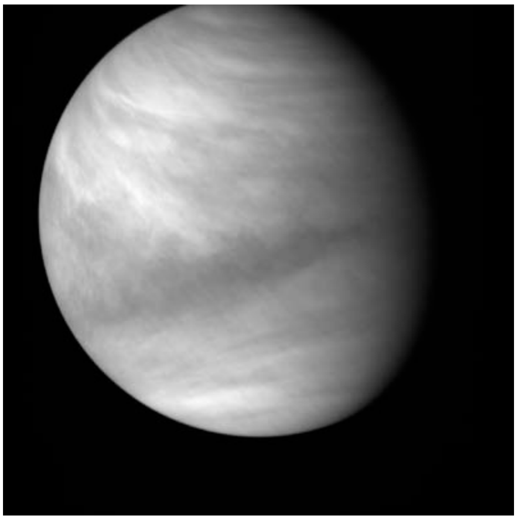
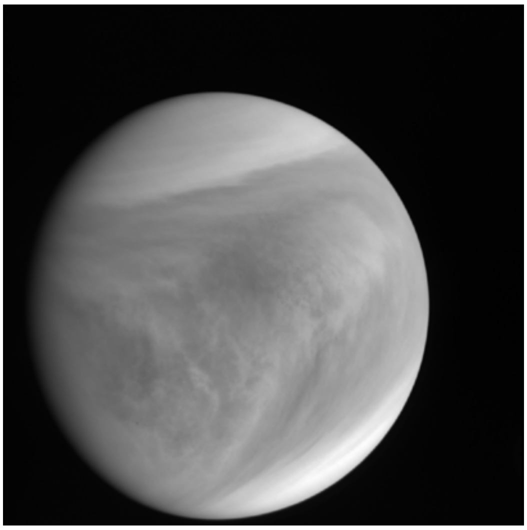
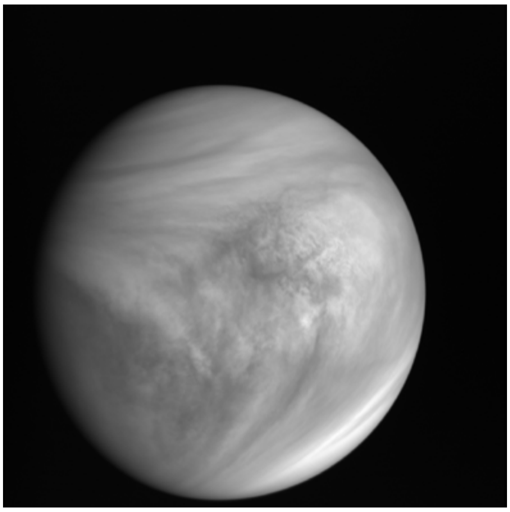


Figure 3. Schematic view of orbit of Akatsuki orbiter around Venus and general observing plan during the ~ 10.5-day orbit.

	
A. 20161120_132347_283	B. 20161120_132721_365
	
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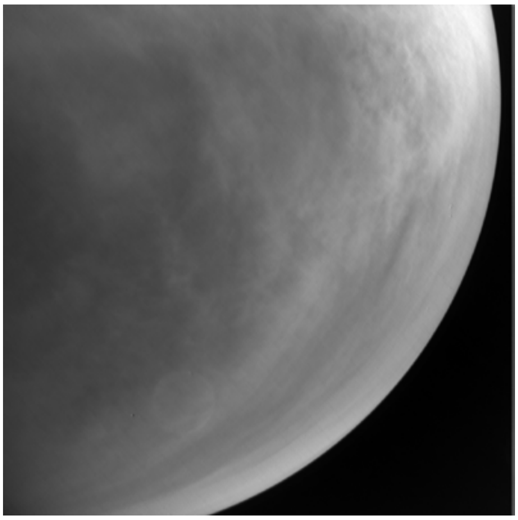	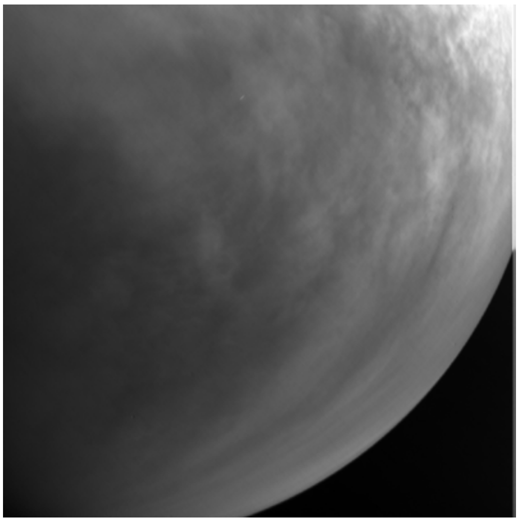
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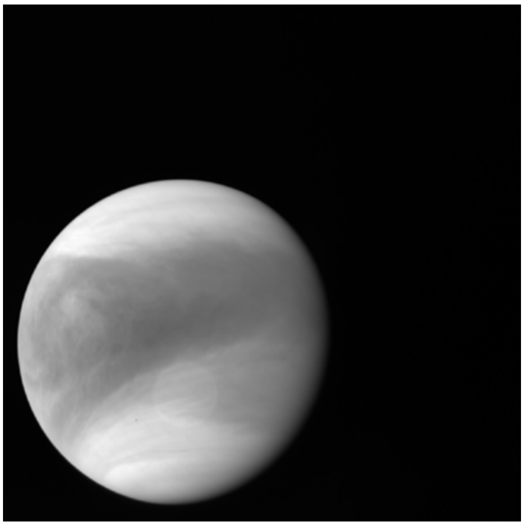

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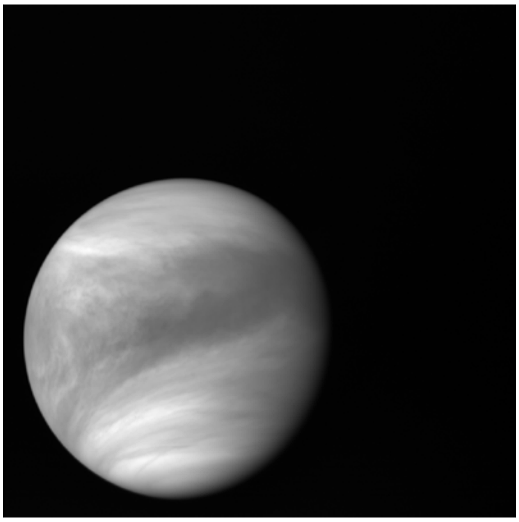

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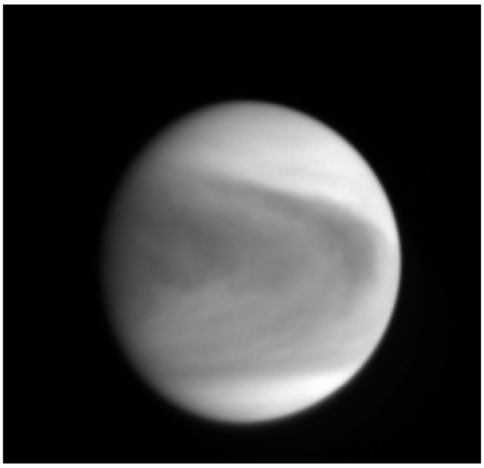

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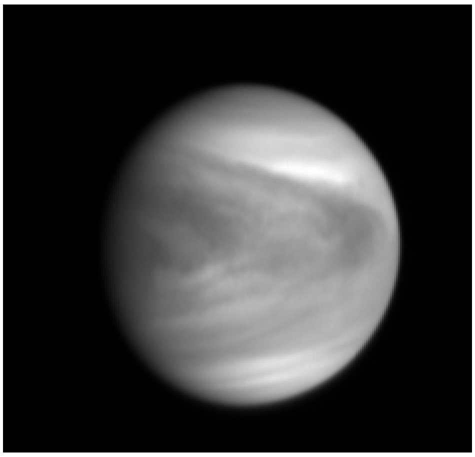
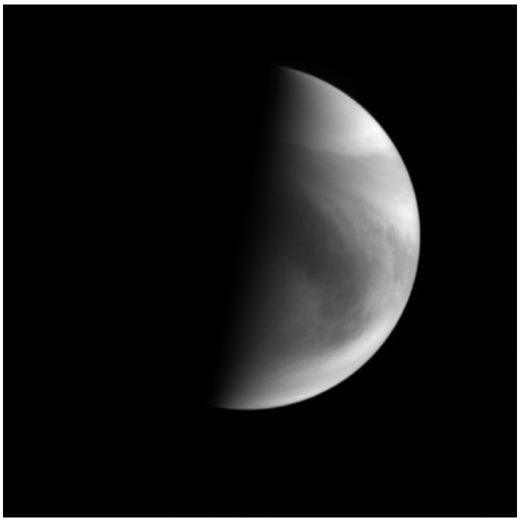


J. 20170120_234944_365



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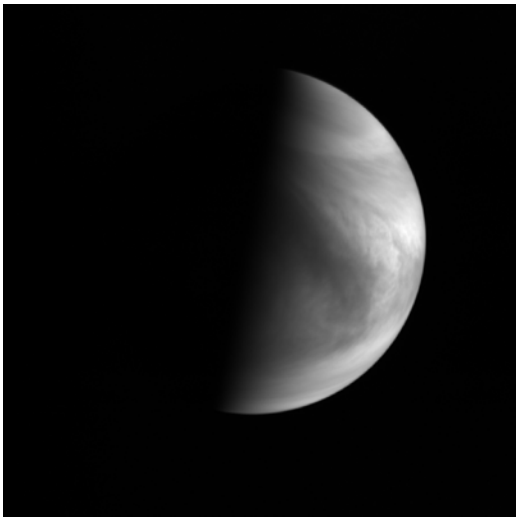

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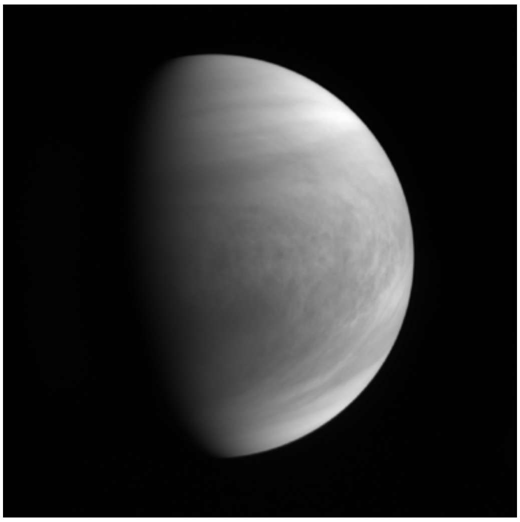
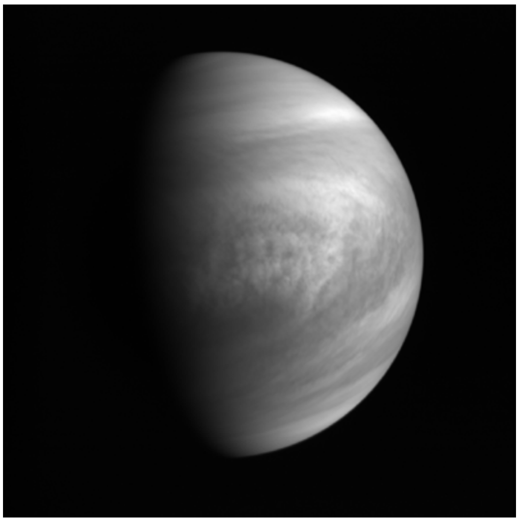
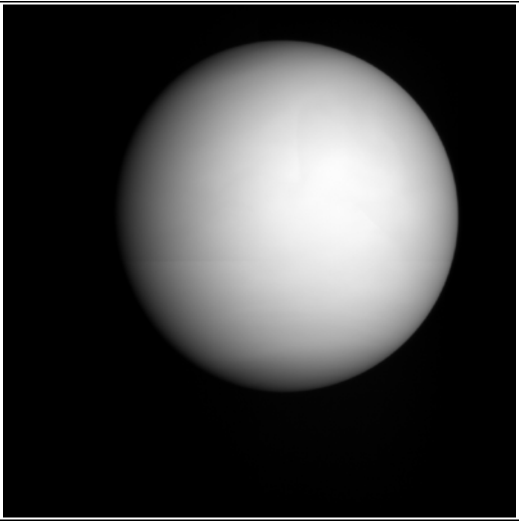
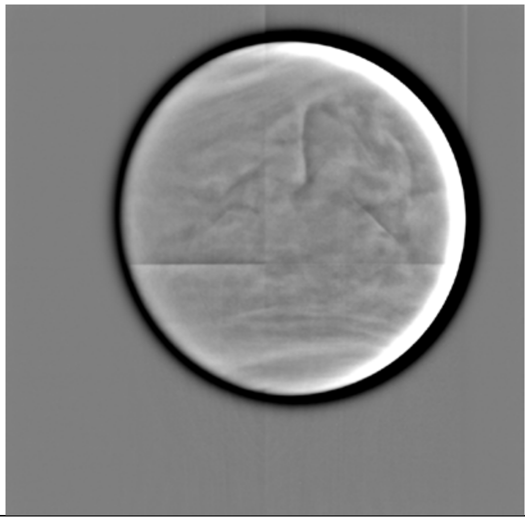
	
M`. 20170114_170111_283_	N. 20170114_170446_365

Figure 4. Selected images from UVI camera taken from the 283 nm (left column) and 365 nm (right column) showing representative features seen in the collection of images taken from Akatsuki. Generally images taken through the 283 nm and 365 nm filters are very close together in time. Simultaneous imaging is not possible from the camera in the two filters, the time difference between them is about 150 seconds, so only at very close approach to Venus is overlap between 283 and 365 nm images is not possible due to the fast movement of Akatsuki it its orbit .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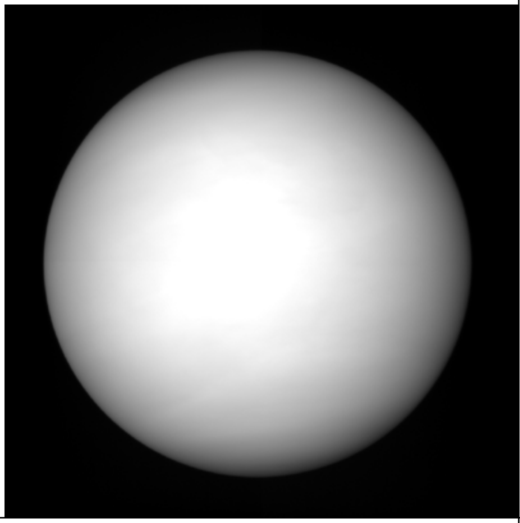	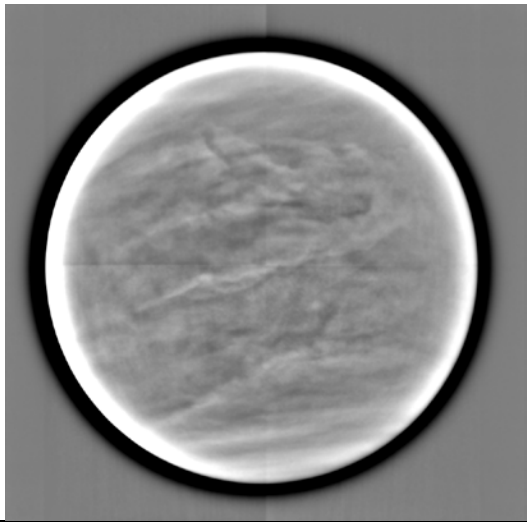
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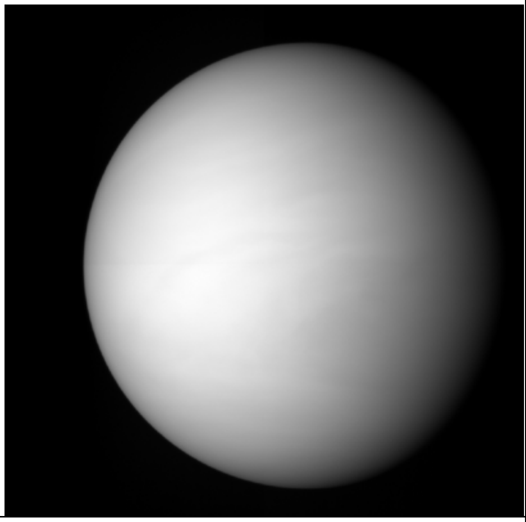
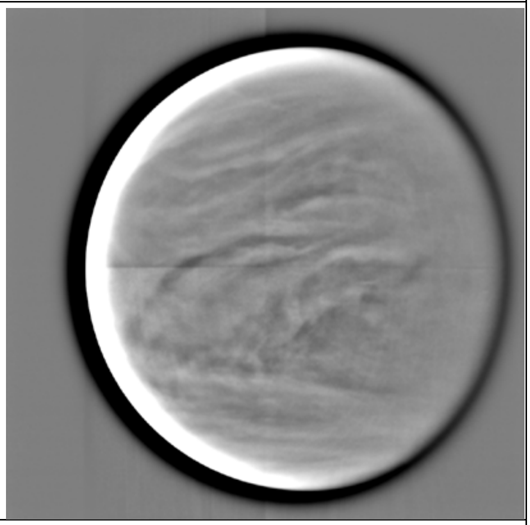
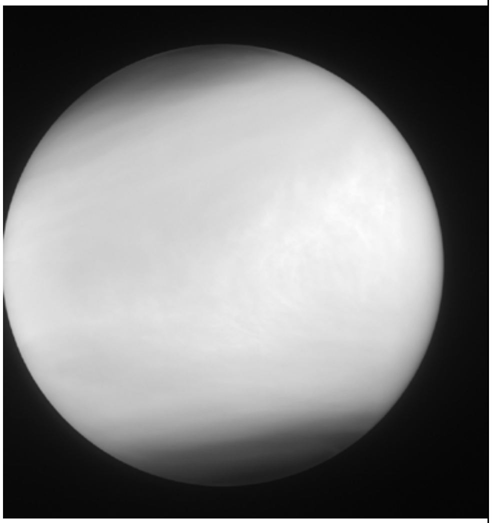
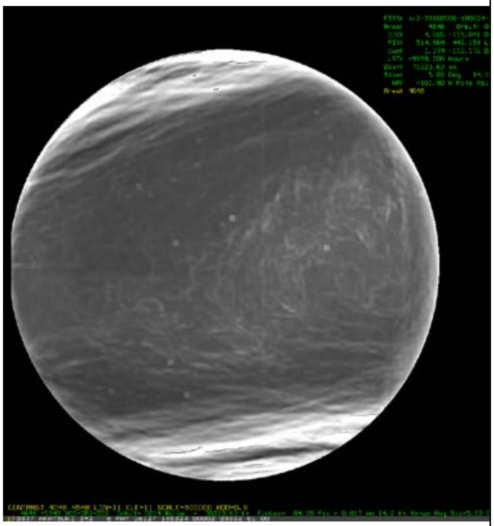
	
E. ir1_20160517_200207_09d_l2b	F. ir1_20160517_200207_09d_l2b_hp

Figure 5. Selected global images taken at 0.97 μm on the day side from the IR1 camera. Calibrated images are shown in the left column and high pass filtered versions are shown in the column on the right. Contrasts are much lower at 900 nm than at 365 nm as expected and the spatial scales and morphology are similar, but the global organization is not as apparent as at 365 nm. In images taken closer to the planet which show the planet at ~ 2-6 km/pixel scale, muted contrasts are seen. This is opposite to what is observed at the ultraviolet wavelengths where the contrasts are much weaker on the very small spatial scales of ~ 5-10 km and are seen only over scales about 10 times larger. Because Akatsuki spends only a short time at close proximity to Venus in its highly elliptic orbit, global coverage at high spatial resolution is not feasible as the field of view of the camera is too small comapred to the angular size of the planet and Akatsuki moves relative to the planet very quickly.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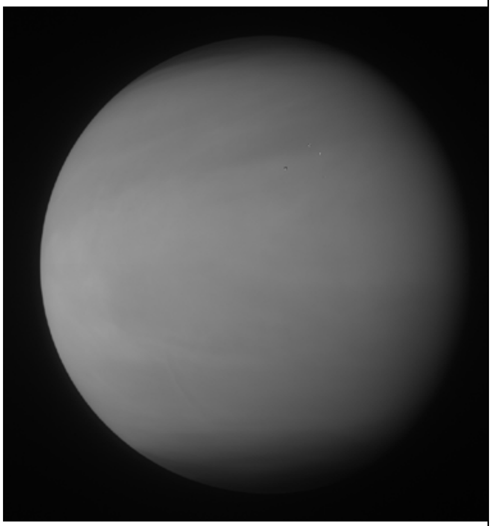	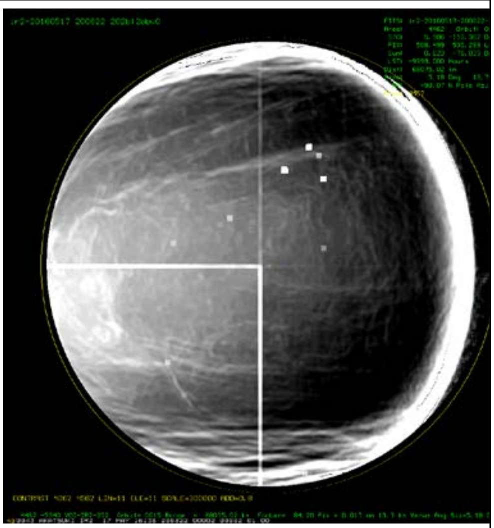
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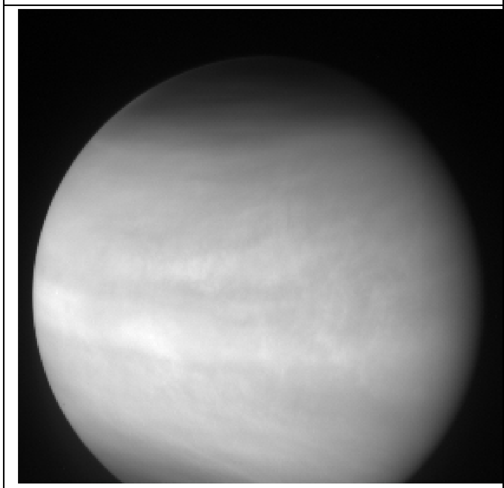
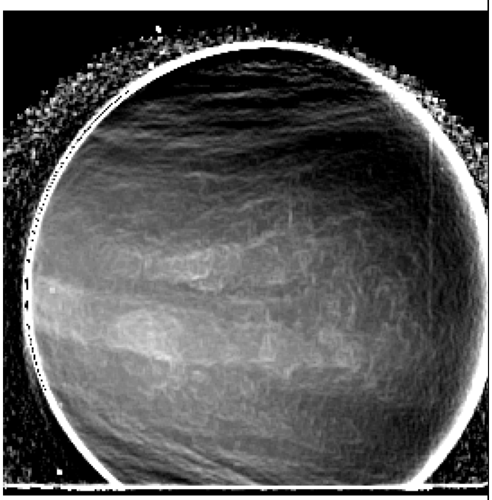
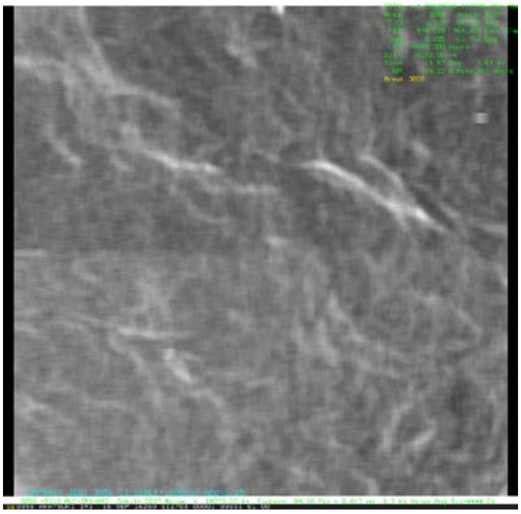
	
C. ir2_20160621_220821_202	

Figure 6. A sample of full disk day side 2.02 µm images from the IR2 camera. The calibrated versions are shown in the left column and contrast filtered versions are shown in the right column to bring out the very low contrast details present in the data.

A close up view of Venus, one the highest resolution ones from Akatsuki orbiter on the day side at ultraviolet and 2.02 µm is shown in Figure 9. The scale is almost 6 km per pixel. Contrasts are seen on sales of about 100 km at 283 and 365 nm, and perhaps on a little larger scale at 2.02 µm, but it may be due to the lower level of contrasts and the dynamic range of the data.



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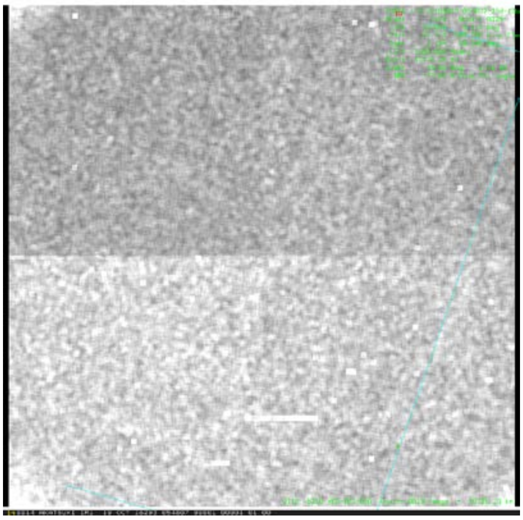

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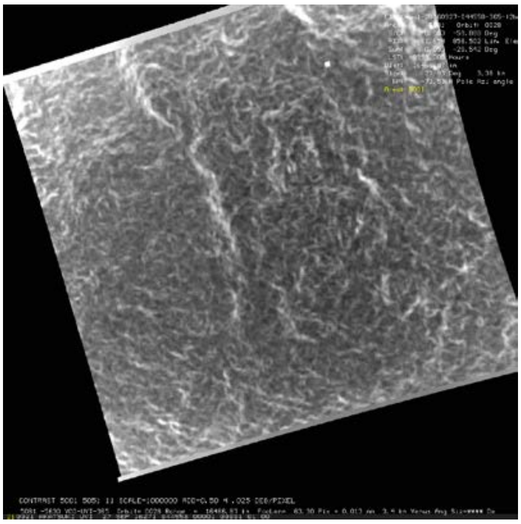

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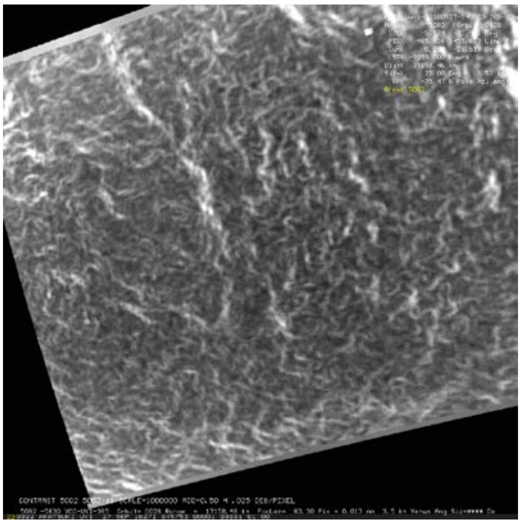

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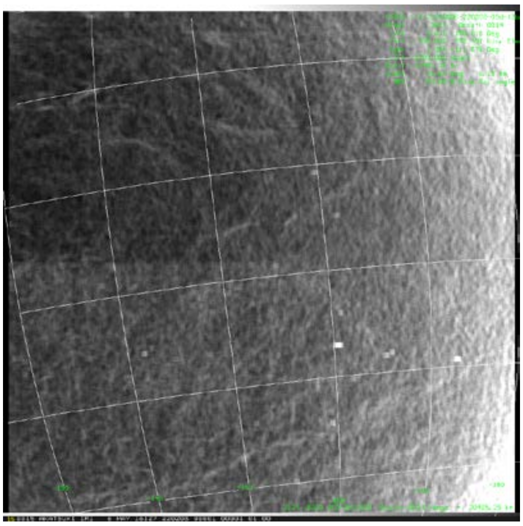
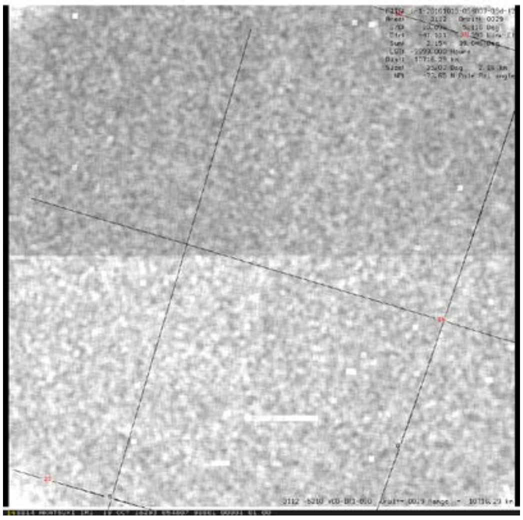
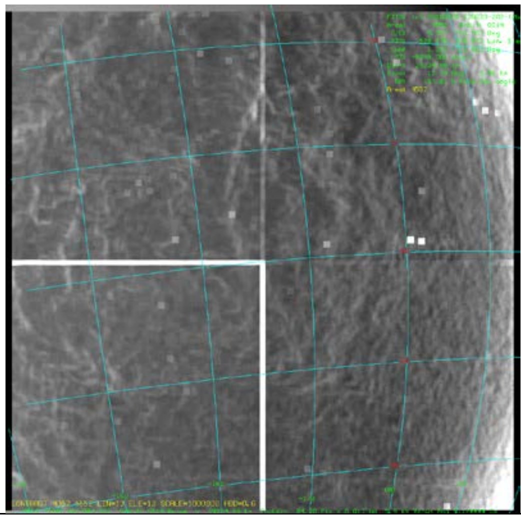


E. ir1_20160508_220208_09d



F. ir1_20160303_212359_09d

Figure 7a. High resolution images from IR1 camera (top and bottom rows) in the 09d filter and two UVI images taken through the 365 nm filter (middle row). Only contrast filtered images are shown to emphasize the details.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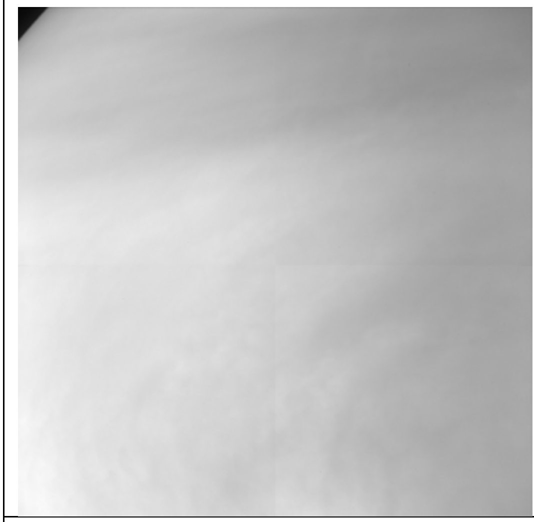	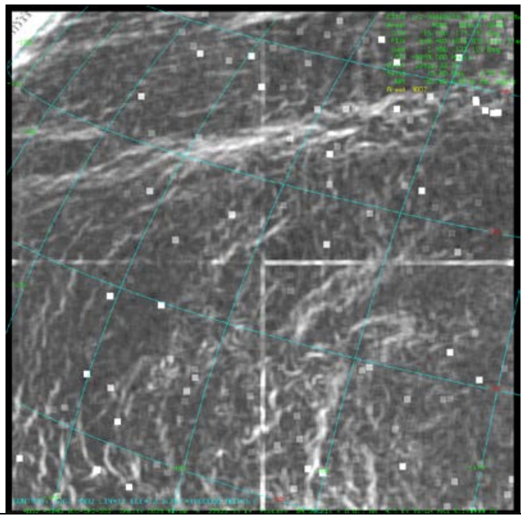
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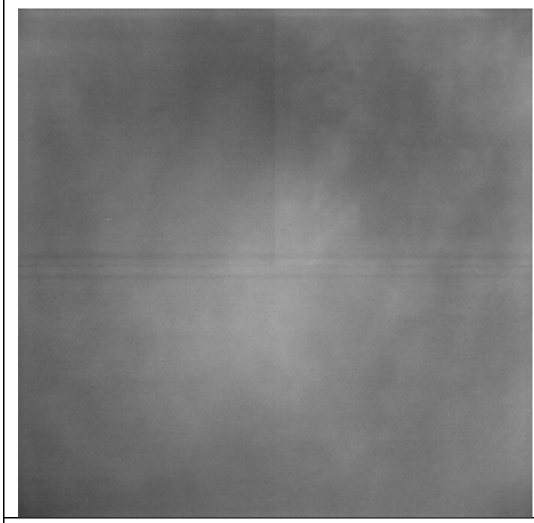
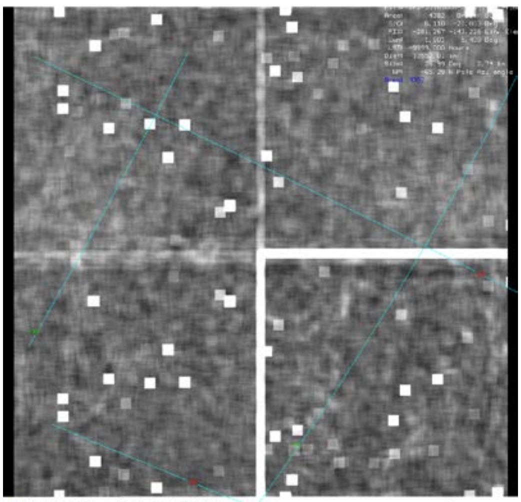
	
C. ir2_20161008_062241_202	

Figure 7b. A sample of high spatial resolution images of the day side 2.02 μm images

from the IR2 camera, each at a pixel scale of approximately 5 km. Very subtle sinuous or string like structures are seen with widths of about 20-40 km and with variable lengths and inclinations to latitude circles are seen in A and B. Image B shows bow like waves seen at ultraviolet wavelengths, often seen with the Y-feature. Image C is devoid of such patterns, but instead shows a bright area surrounded by a poorly defined dark ring which is suggestive of the glory feature seen on Venus at other wavelengths but the phase angle is far from 0° and is believed to be due to the electronic noise due to the cross-talk between the readout of the four quadrants of the image (Satoh et al., this issue).

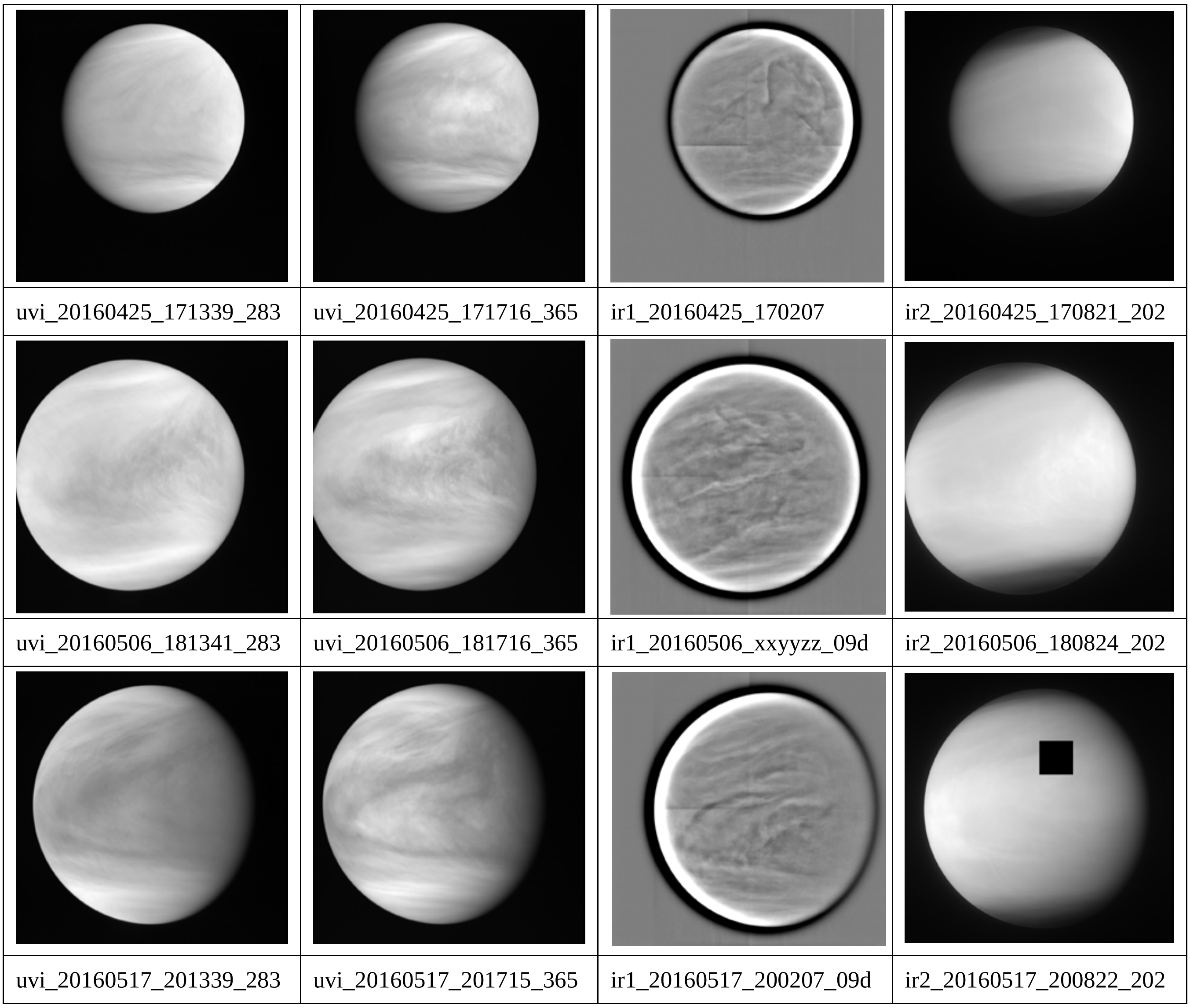


Figure 8. Concurrent views of the dayside hemisphere of Venus at 283, 365, 900 and 2020 nm. The 900 nm images are shown after applying a high pass filter to bring out subtle detail. The high latitude regions appear darker at 2020 nm due to the increased absorption by CO2 indicating somewhat lower cloud tops. The black square in the May 17 IR2 image is an artifact of the processing.

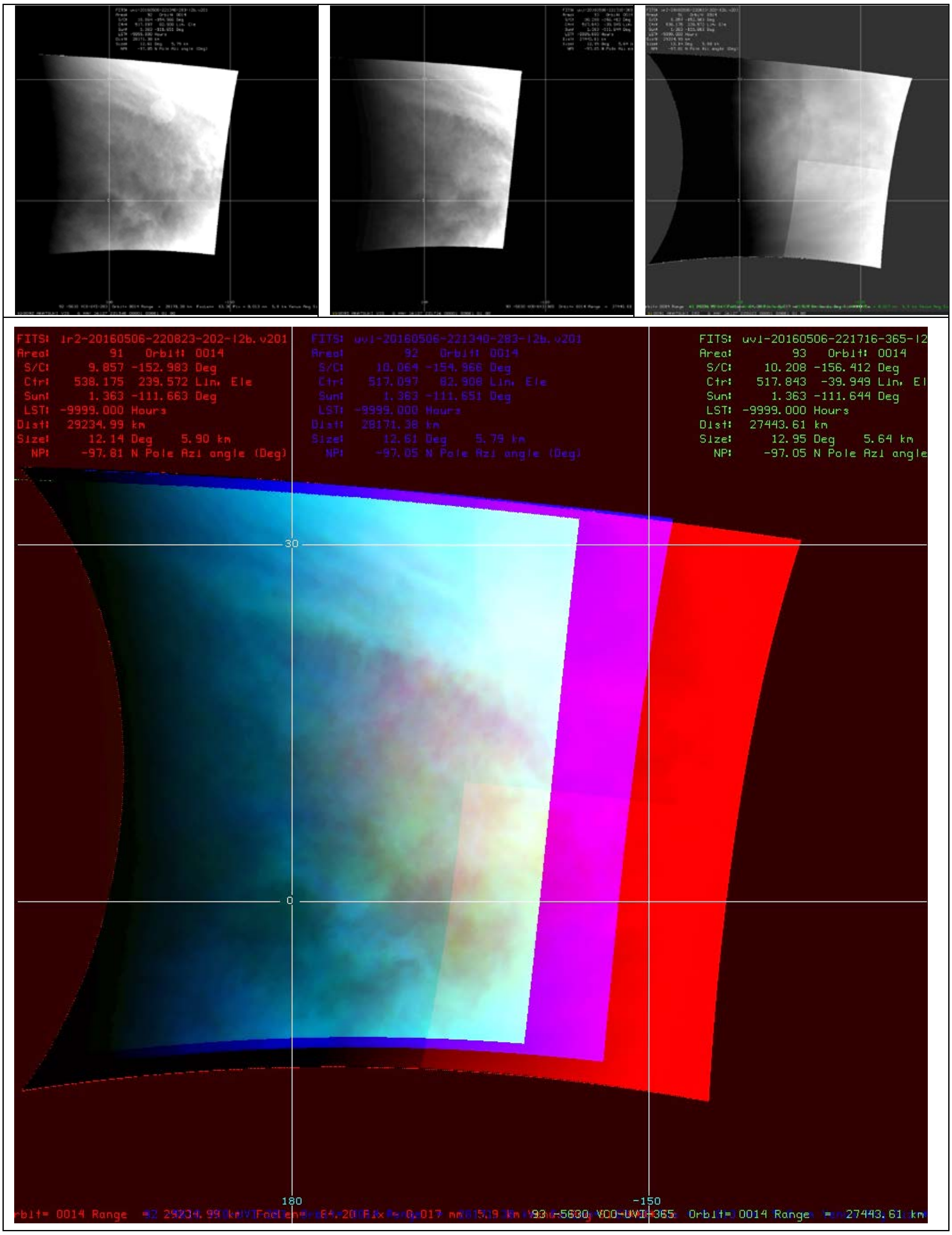
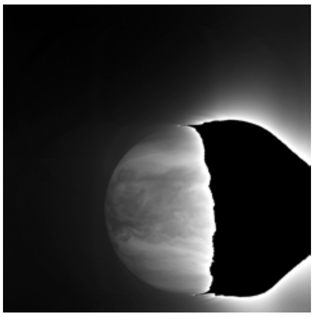
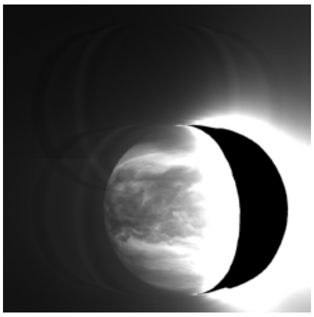
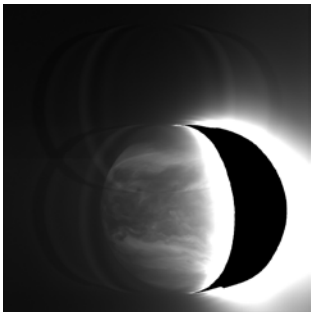


Figure 9. A high resolution view of Venus at 283 nm, 365 nm and 2.02µm (~ 6 km per pixel) from Akatsuki UVI and IR2 cameras on 6 May 2016. The lower right quadrant boundary of the 2.02 µm image is an artifact. The lower right image is a color

composite of these images in a latitude-longitude view (Red- 2.02 µm, Green- 365 nm and Blue – 283 nm). The oval shaped bright spot seen in the 283 image is an artifact.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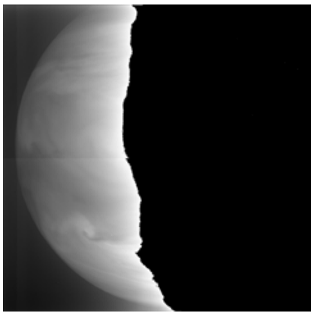	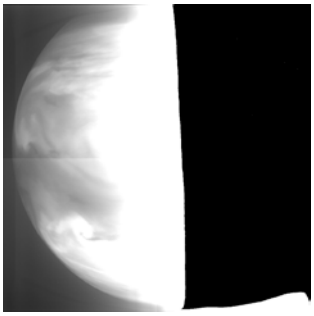	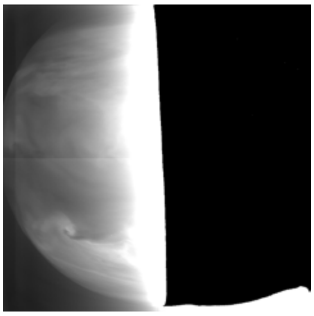
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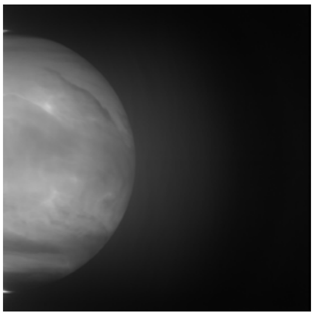	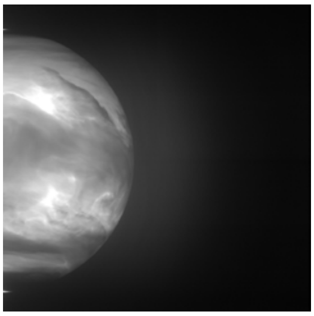	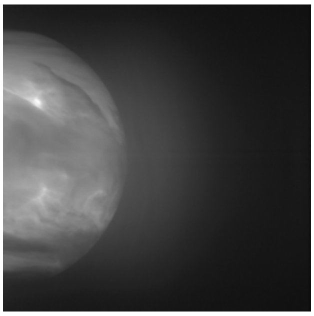
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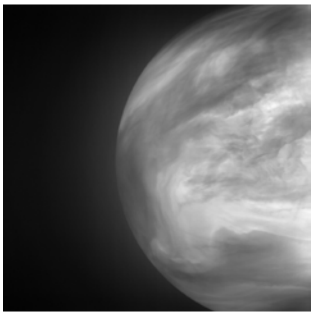	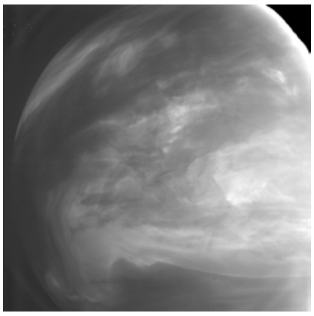	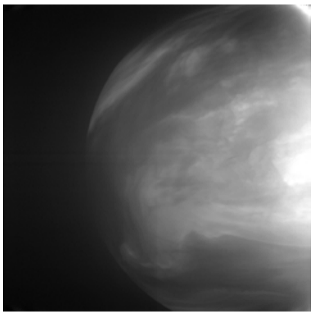
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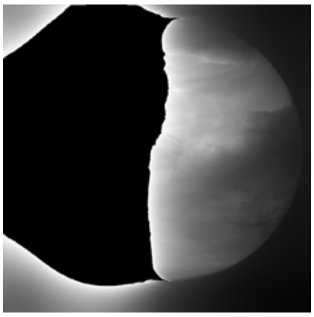		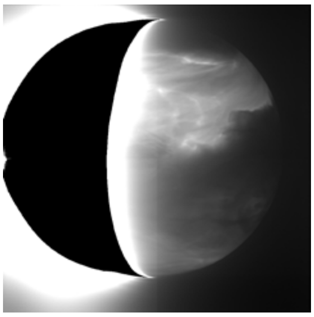
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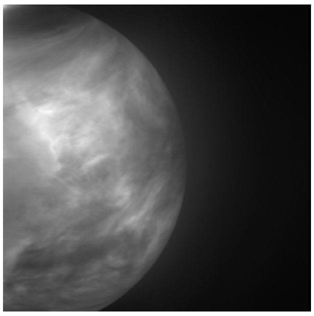	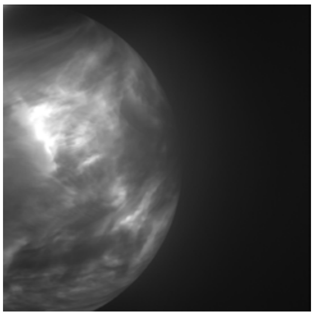	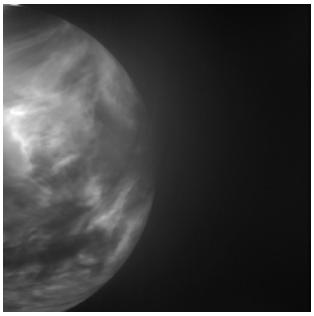
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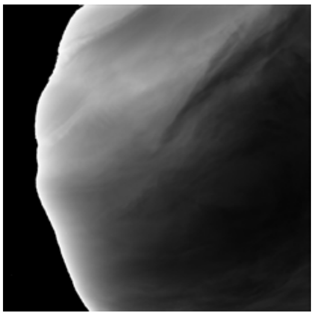	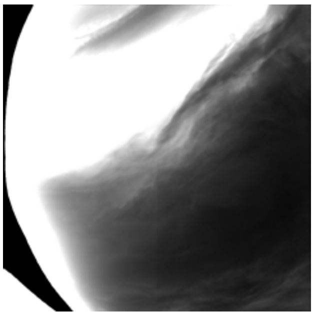	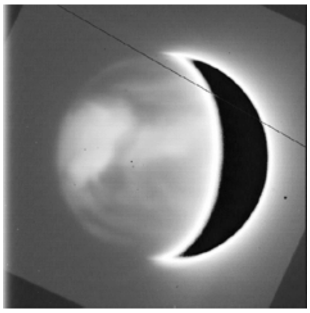
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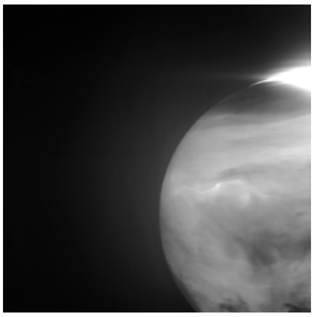
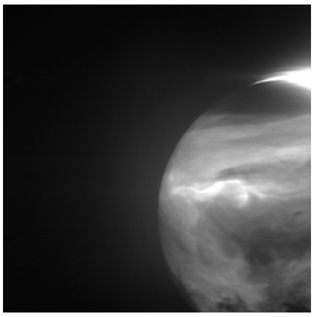
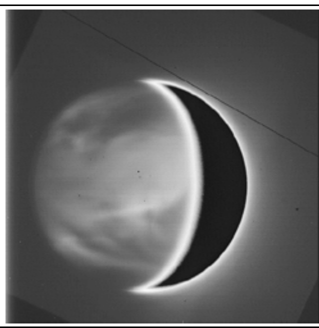
		
V ir2_20161030_080211_174	W 20161030_080333_226	X IRTF Cont_K April 28

Figure 10. Selected images at 1.74, 2.26 and 2.32 μm taken from the IR2 camera on the night side of Venus. Images U and X are part of supplemental IRTF images for IR2.

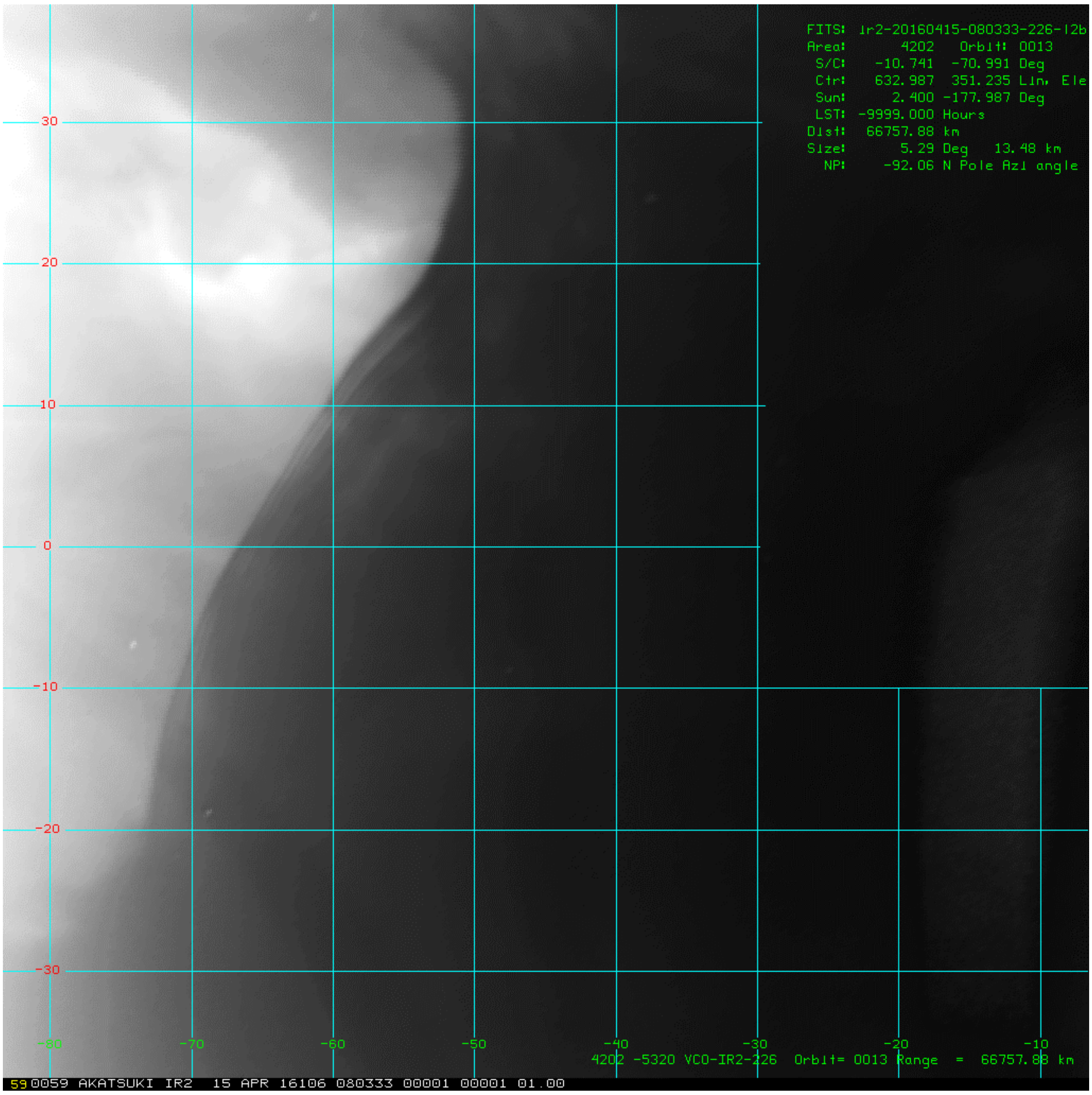


Figure 11a. A latitude-longitude map of 2.26 µm nightside image obtained from the IR2 camera on April 25 showing an unusual sharp boundary in the intensity. Such sharp bounaries are seen on Earth only in water vapor channels, thereby showing the dry and moist airmasses (Figure 11b).

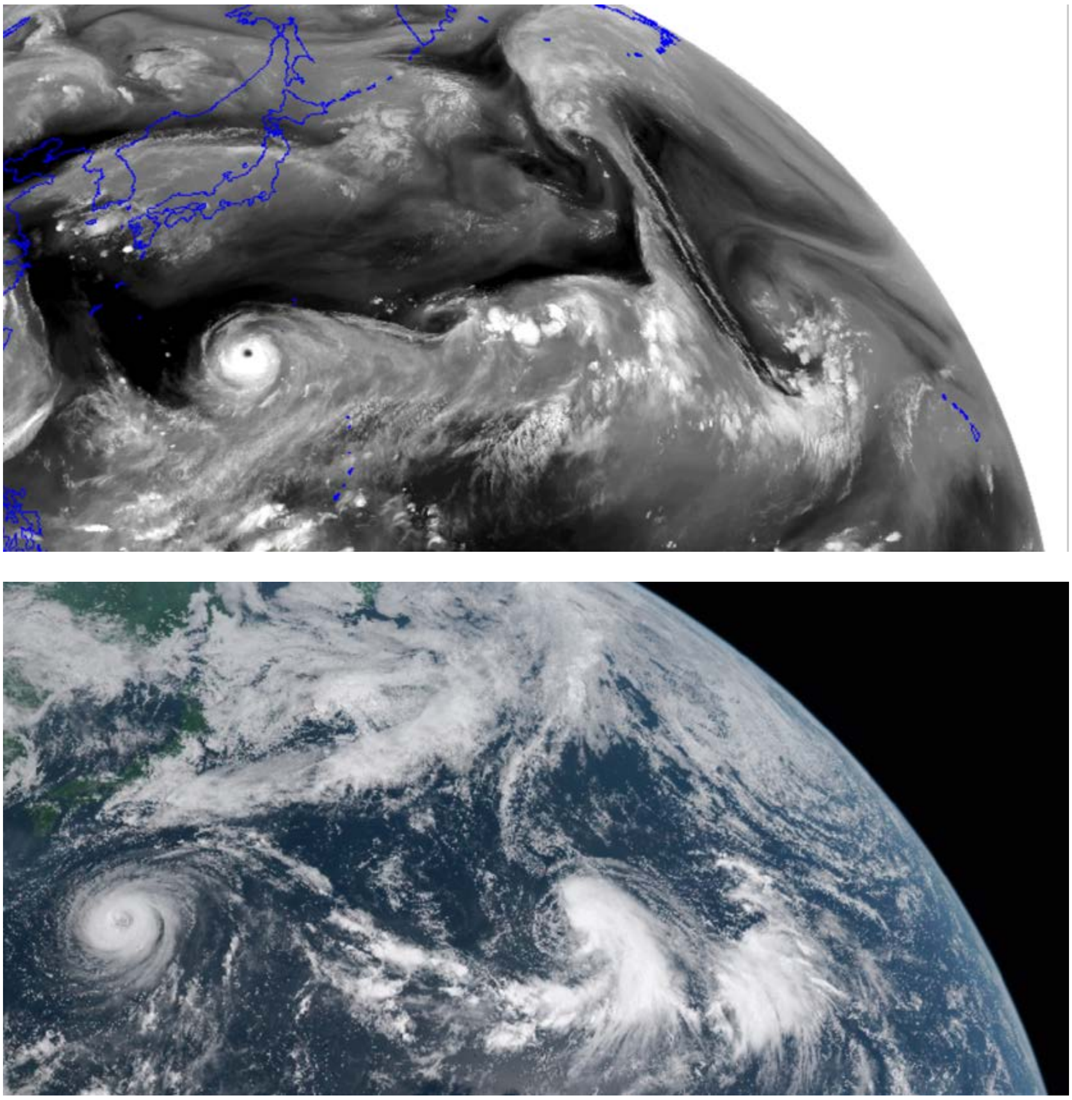


Figure 11b. Sharp bounbaries are also seen in iamges of Earth taken from weather satellites in the water vapor channel (top). This image taken from Himari on 1 August 2017 at 23:50 UT in the 6.9 μm channel shows several sharp boundaries depicting different air masses with different lower troposhperic water vapor amounts. The bottom image is a RGB composite view taken at the same time where the boundary is not so easily discerned but can be inferred from the destruction of the clouds due to entrainment of the the dray air in the western half of the cyclonic region (central part of the color image). By analogy, the shart boundaries seen on Venus in the IR2 night time

images may suggest different “air masses” due to differing trace gas abundance(s) on Venus in the Venus cloud layer.

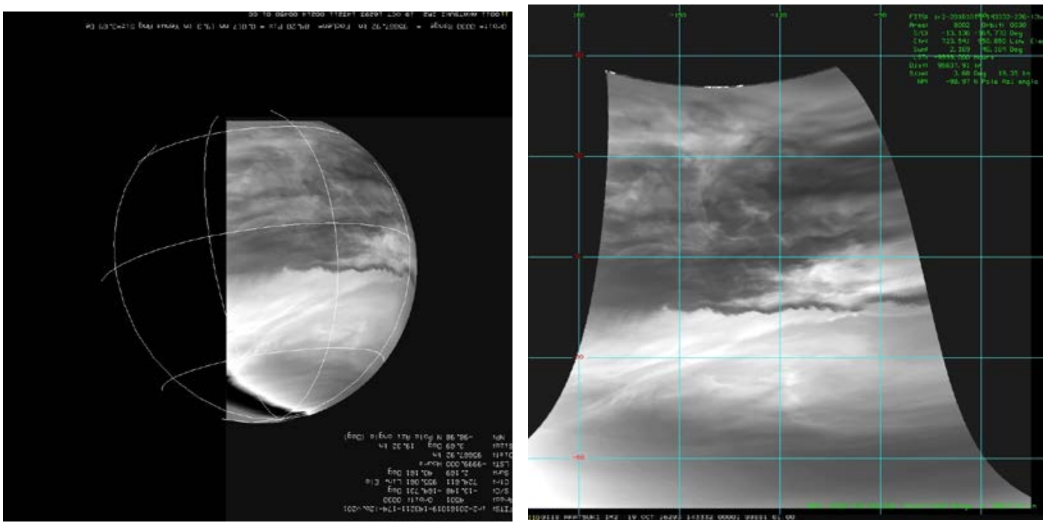


Figure 12. This 2.32 µm image (ir2_20161019_143211_226) suggests a wave like boundary between cloud masses at some unknown altitude.

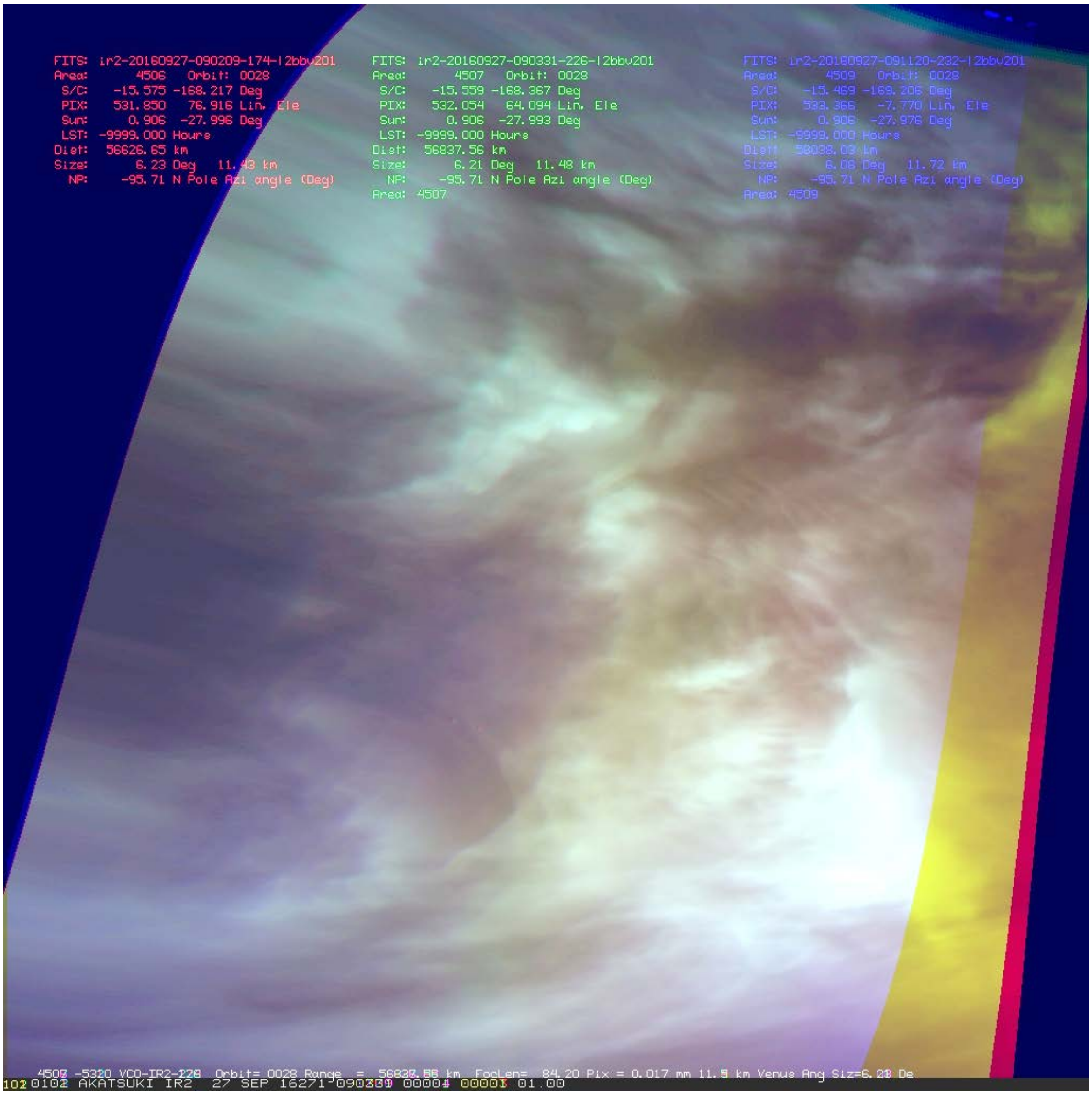
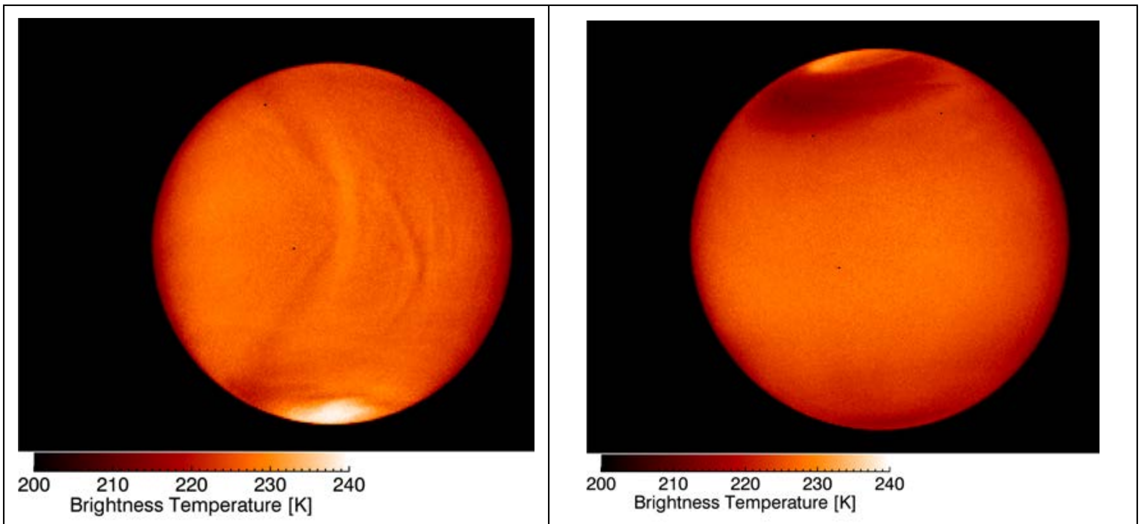


Figure 13. Subtle variations in the opaticities are revealed in this color composite generated from mapped 1.74 μm (red), 2.26 μm and 2.32 μm images. The image scale is 0.1°/pixel in latitude and longitude.



A. 20160723_073128_pic	B. 20160506_182053_pic

Figure 14. Representative images of Venus taken by the LIR camera at 8-12 µm. Panel A shows the standing gravity waves discovered by Akatsuki from such observations (Fukuhara et al., 2017), while B shows Venus when the standing wave is not present. Generally the equator ward edge of the vortex over the poles is seen in all the LIR images depicting its temporal evolution due to the vortex dynamics (Garate-Lopez et al., 2015; Garate-Lopez et al., 2013; Limaye et al., 2009; Piccioni et al., 2007).

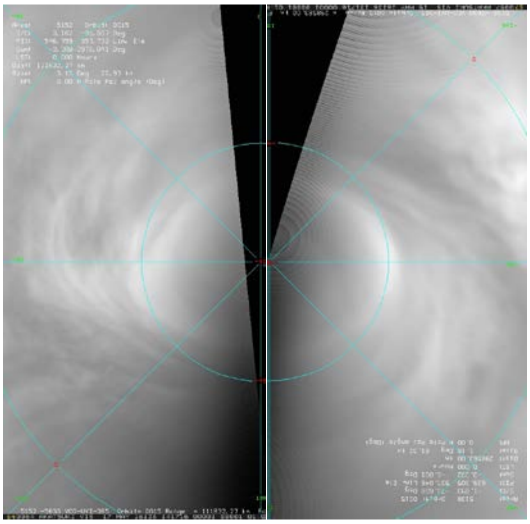
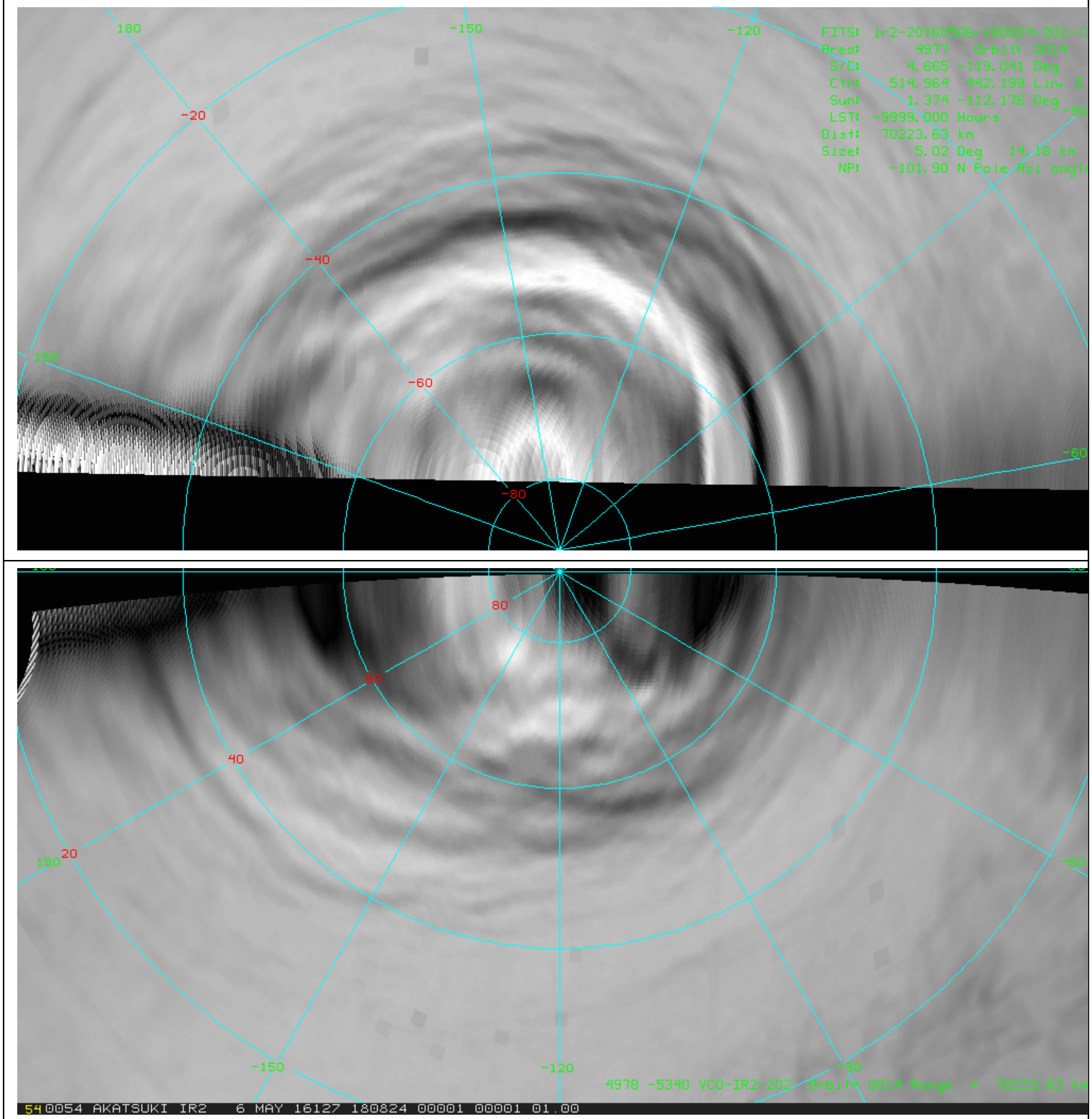


Figure 15a. The cloud cover at the ultraviolet shows the same vortex morphology over

both hemispheres. This composite view is from two 365 nm images taken on 15 May (right) and 17 May (left) on orbit 15 of Akatsuki and show the southern hemisphere vortex. The 15 May image is rotated by 180°. A similar vortex is seen over the northern pole.



Ir2_20160506_180224_202

Figure 15b. North (bototn) and south (top) hemispheres in polar stereographic projection of a 2.02 µm contrast filtered image with overlaid latitude and longitude grid.. The calibrated image was first subjected to a contrast filter to bring out the local structures and then projected. Although the pattern at higher latitudes show patterns similar to the spiral arms of the vortex seen at ultraviolet, there is considerable amount detail in the core region visible.

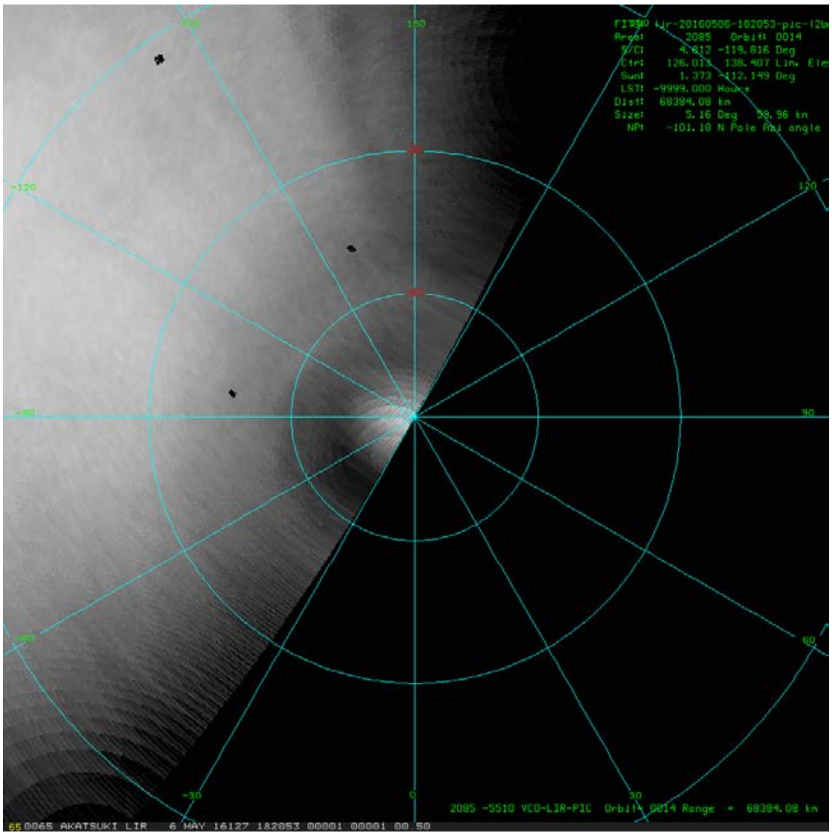


Figure 15c. Polar stereographic view of the northern hemisphere of the image B of Figure 14, also showing the warmer (deeper) core region of the vortex. This is consistent with the 2.02 µm image.

Uncategorized References

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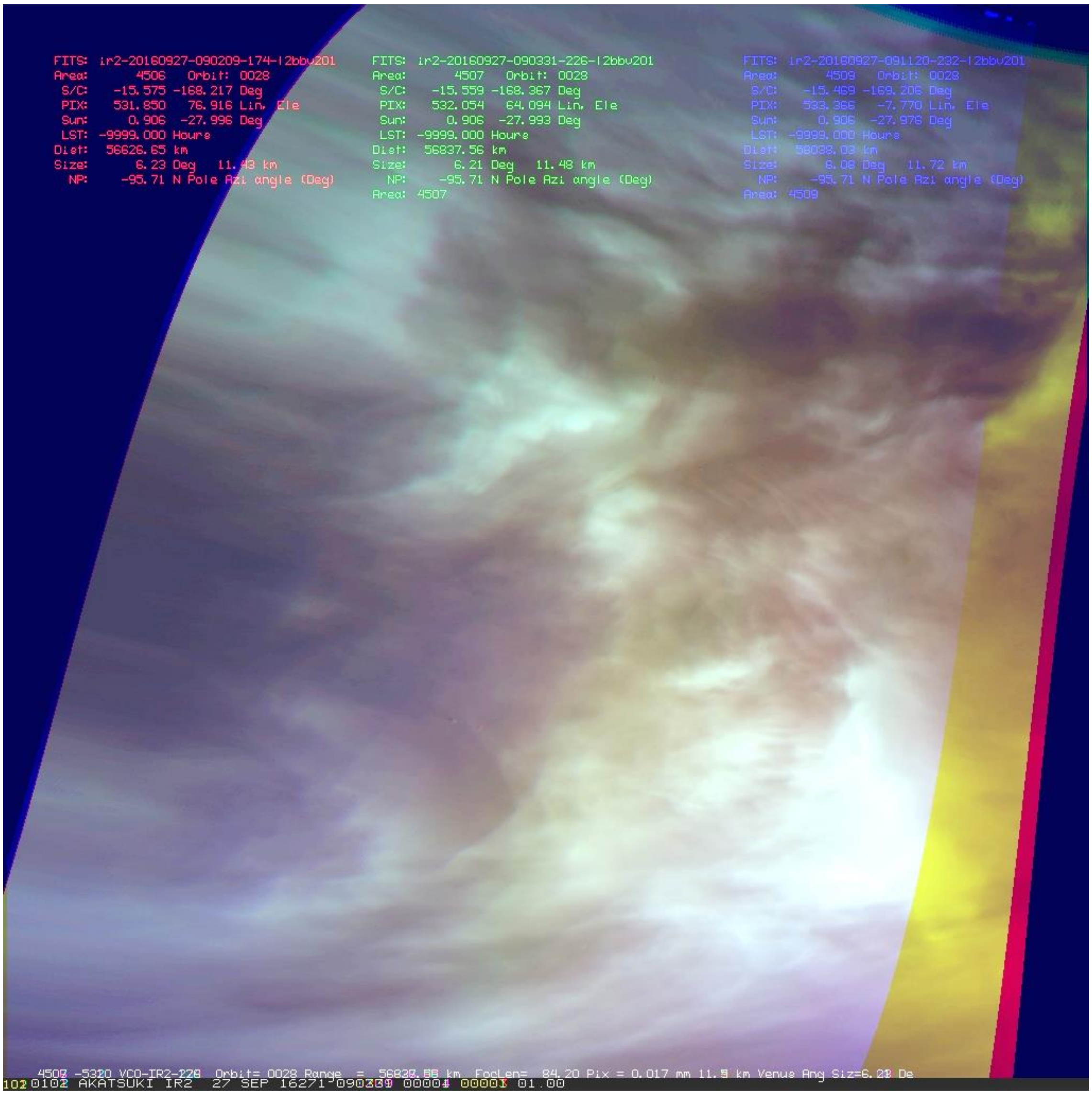

Akatsuki global images of Venus on the day and night side are providing new insights into the behavior and properties of clouds on Venus and informing us about its dynamic atmosphere.

Venus' Spectral Signatures and the Potential for Life in the Clouds

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Abstract

The lower cloud layer of Venus (47.5-50.5 km) is an exceptional target for exploration due to the favorable conditions for microbial life including moderate temperatures and pressures (~60 ˚C and 1 atm), and the presence of micron-sized sulfuric acid aerosols. Nearly a century after the ultraviolet contrasts of Venus' cloud layer were discovered using Earth-based photographs, the substances and mechanisms responsible for the changes in Venus' contrasts and albedo are still unknown. While current models include sulfur dioxide and iron chloride as the ultraviolet absorbers, the temporal and spatial changes in contrasts, and albedo between 330-500 nm, remain to be fully explained. Within this context, we present a discussion regarding the potential for microorganisms to survive in Venus' lower clouds and contribute to the observed bulk spectra. In this hypothesis paper, we provide an overview of Venus spectroscopy, characterize the spectral and physical properties of terrestrial biological materials compared to Venus' clouds, review the potential for an iron and sulfur-centered metabolism in the clouds, and discuss conceivable mechanisms of transport from the surface towards a more habitable zone present in the lower clouds. Together, our hypothetical lines of reasoning suggest that particles in Venus' lower clouds contain sufficient mass balance to harbor microorganisms, water, and solutes, and potentially sufficient biomass to be detected by optical methods. As such, the spectral overlaps between Venus and terrestrial biomolecules potentially warrant further investigations into the prospect of biosignatures in Venus' clouds.

Introduction

The habitability of Venus' clouds has been a subject of discussion for several decades, but has gained limited traction as a popular target in astrobiology research. Initially stirring excitement, Cockell (1999) concluded that the conditions between the lower and middle Venus atmosphere were conducive to (terrestrial) biology, and that conditions in the higher Venus altitudes would freeze but not necessarily kill microorganisms. Since then, subsequent studies have highlighted the potential for life in Venus' cloud layers due to favorable chemical and physical conditions, including the presence of sulfur compounds, CO_2, and water, and moderate temperatures (0-60 ˚C) and pressures (~0.4-2 atm) (Schulze-Makuch et al., 2004; Schulze-Makuch & Irwin, 2002). In this hypothesis paper, we further consider these conditions and examine the potential for microorganisms to survive in the clouds and contribute to the bulk spectral properties of Venus.

Overview of Venus Spectroscopy

Comparisons of spectral measurements (**Figure 1**) obtained from the Pioneer Venus, Magellan, Galileo, and Akatsuki missions show several differences in albedo across the spectrum from the UV (**Figures 1A-C**) and the visible (**Figures 1D-F**) to near infrared wavelengths (**Figures 1G-I**). Venus is globally covered in clouds and devoid of contrasts in the visible and infrared wavelengths in day side images (**Figures 1D-G**). Rather, contrasts in the cloud cover are observed only at wavelengths shorter than blue in reflected sun light (**Figures 1A-C**), and at near infrared wavelengths (1.7-2.4µm) on the nightside (**Figures 1G & 1H)**. Despite spacecraft investigations from orbit and entry probes, the chemical and physical properties of these contrasts are still unknown, including the lack of mixing, the identities of the contrasting substances, the sources of these substances, and any potential sinks. Thermal infrared images (10-

15 µm) show small scale (~50 km) contrasts of less than 2 K in brightness temperature on the day and night hemispheres at all latitudes, except poleward of ~65° latitude in both hemispheres. At these latitudes, Hadley circulation is presumed to suppress the cloud tops due to down-welling in polar regions, as observed near the top and bottom of the Venus images (**Figure 1I**). In contrast, clouds on Earth are often observed in satellite images as discrete features with clear air in between at visible and short to thermal infrared wavelengths (**Figures 1 J-O**). Unlike on Earth, the observed contrasts in Venus' global cloud cover vary with wavelength from visible to infrared (Limaye et al., 2017) in morphology as well as magnitude as shown in **Figures 1A-C, 1G, and 1H,** Venus and **Figures 1 J-O,** Earth.

The Venus UV contrasts were first observed in Earth based photographs (Ross, 1928) and subsequently characterized by ground based polarimetry (Hansen & Hovenier, 1974), spectroscopy (Barker, 1978; Barker, 1993), remote spacecraft observations (Kawabata et al., 1980; Titov et al., 2008) and entry probes (Esposito et al., 1983); Knollenberg et al. (1980); (Knollenberg, 1984; Knollenberg & Hunten, 1980). Together, these studies indicate that the global cloud cover is composed of sulfuric acid droplets (~1.1 µm equivalent radius) in a mixture consisting mostly of small particles (~0.2-0.3 µm equivalent radius), with larger particles (~2-8 µm diameter) present at lower altitudes (Knollenberg & Hunten, 1979). In addition, slight differences in cloud particle properties at the polar regions have been inferred from the Venus Express data (Wilson et al., 2008).

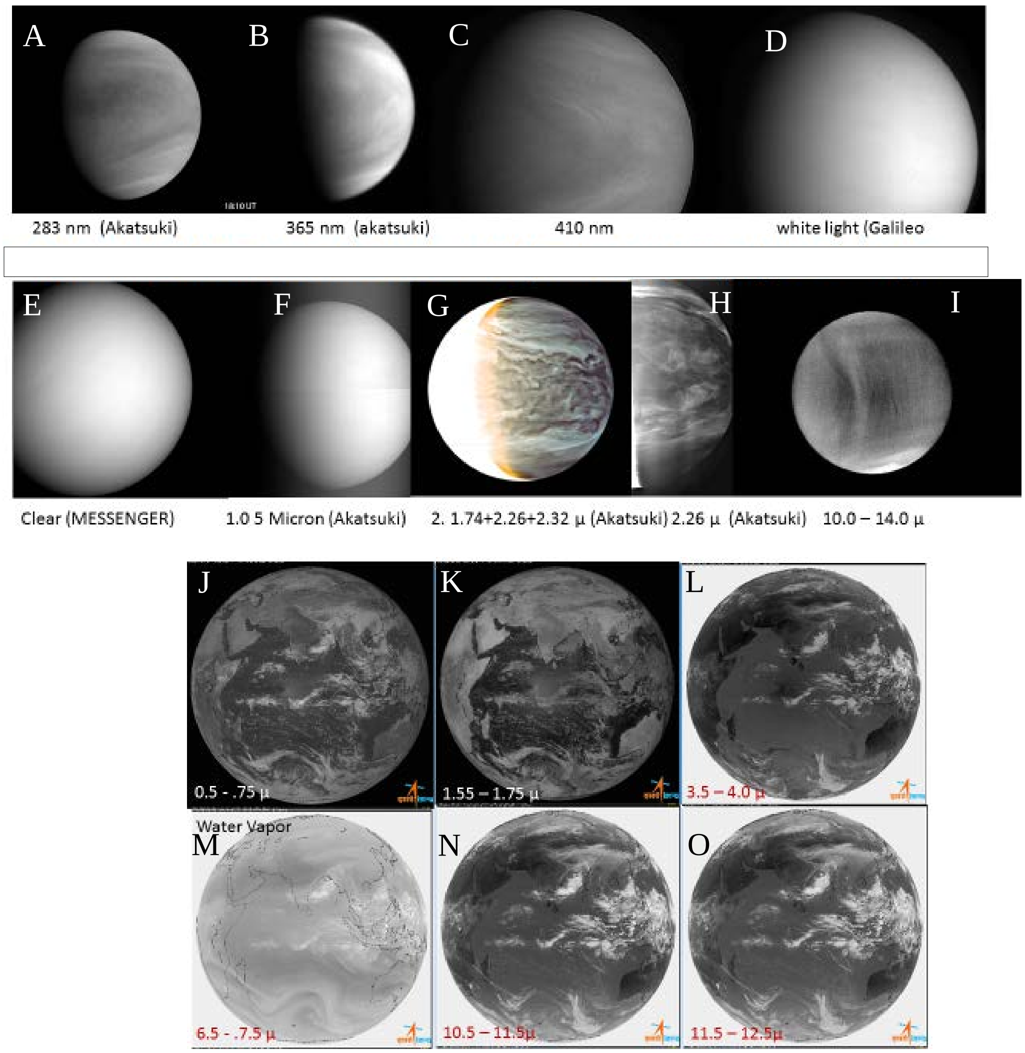


Figure 1. *Difference in spectral contrasts of Venus at the wavelengths of (A)283 nm and , (B) 365 nm (Akatsuki,), (C) 410 nm,(D) white light (Galileo, Belton et al. (1991)), (E) clear (MESSENGER, Hawkins et al. (2009)), (F) 0.5 µm (Akatsuki), (G) 1.74+2.26+2.32 µm (Akatsuki), (H) 2.26 µm (Akatsuki), and (I) 10.0-14.0 µm; and spectral contrasts of Earth at the wavelengths of (J) 0.5-0.75 µm, (K) 1.55-1.75 µm,(L) 3.5-4.0 µm,(M) 6.5-7.5 µm, (N) 10.5-11.5 µm, and (O) 11.5-12.5 µm (ISRO,R. Katti et al. (2006)). Akatsuki data are available from: https://www.darts.isas.jaxa.jp/planet/project/akatsuki/*

Provided in **Figure 2** is a collective summary of Venus spectra between 200-1000 nm, including global geometric or spherical albedo estimates (Irvine, 1968; Moroz et al., 1985; Travis, 1975) and measurements from ground based telescopes (Barker et al., 1975), and MESSENGER spaceraft during the second Venus fly-by (Perez-Hoyos et al., 2013). Also shown is the calculated difference between the VIRA cloud model and the MESSENGER spectra (updated from Perez-Hoyas, 2013), which gives an indication of the spectral absorption by the unknown materials in the clouds of Venus. We note here that the original identification of the sulfuric acid composition of the Venus cloud particles was derived by matching the index of refraction, required for matching the phase dependence of disk integrated polarization at different optical wavelengths (Hansen & Hovenier, 1974), and not by spectral identification. Interpretation of Venus' UV and IR spectra, along with questions about the cloud composition and ultraviolet absorbers, are summarized by (Krasnopolsky, 2006) and in chapters within the review books on Venus (Hunten et al., 1983) and Venus II (Bougher et al., 1989). Herein, we summarize briefly the pertinent cloud properties which must play a part in the absorption of incident sunlight and the observed contrasts. Travis (1975) pointed out that the spectral dependence of albedo and cloud contrasts are different, and thus indicate at least two different absorbers. Pollack et al. (1980) identified gaseous sulfur dioxide as a potential absorber, and ruled out many other suggested candidates due to insufficient spectral overlap. Esposito and Travis (1982) suggested from analysis of the polarization data obtained from the Pioneer Venus Orbiter that the differential polarization between bright and dark UV features could not be explained by haze abundance variations, and favored a chemical model where water vapor and molecular oxygen are depleted at the cloud tops.

Zasova et al. (1981) built upon Kuiper (1969) proposed presence of incompletely hydrated $FeCl_2$ in the clouds, and offered that sulfur dioxide (below 330 nm) along with ferric chloride ($FeCl_3$) (above 330 nm) could explain the observed lowered albedo below 500 nm. The partial contribution of sulfur dioxide to UV absorption of incident solar radiation has been observed from Venus Express observations (Lee et al., 2015b), as well as those from Hubble Space Telescope (Jessup et al., 2015), and can also be discerned from differences in the spectra of Venus at 283 nm (where there is some absorption by SO_2) and 365 nm (where the contrast peaks and SO_2 does not absorb) taken by Akatsuki (**Figures 1A & 1B**). Based on Venus Express measurements, analysis of the glory feature observed in unpolarized (Markiewicz et al., 2014) and polarized light (Rossi et al., 2015) have yielded values for index of refraction larger than the those inferred by Hansen and Hovenier (1974). Markiewicz et al. (2014) suggested that presence of $FeCl_3$ attached to the sulfuric acid droplets, which may also act as cloud condensation nuclei, could explain the higher indices of refraction. Krasnopolsky (2017) concluded that sulfur aerosols cannot be the UV absorber since the required abundance and vertical profile were incompatible with Venera 14 observations; however, the presence of $FeCl_3$ was compatible with contributions towards the higher values of indices of refraction inferred by Markieicz et al. (2014). Nevertheless, some doubt remains whether analysis of glory features can lead to an accurate inference of the index of refraction (Laven, 2008) values between 1.07 and 1.7, as is the case for Venus.

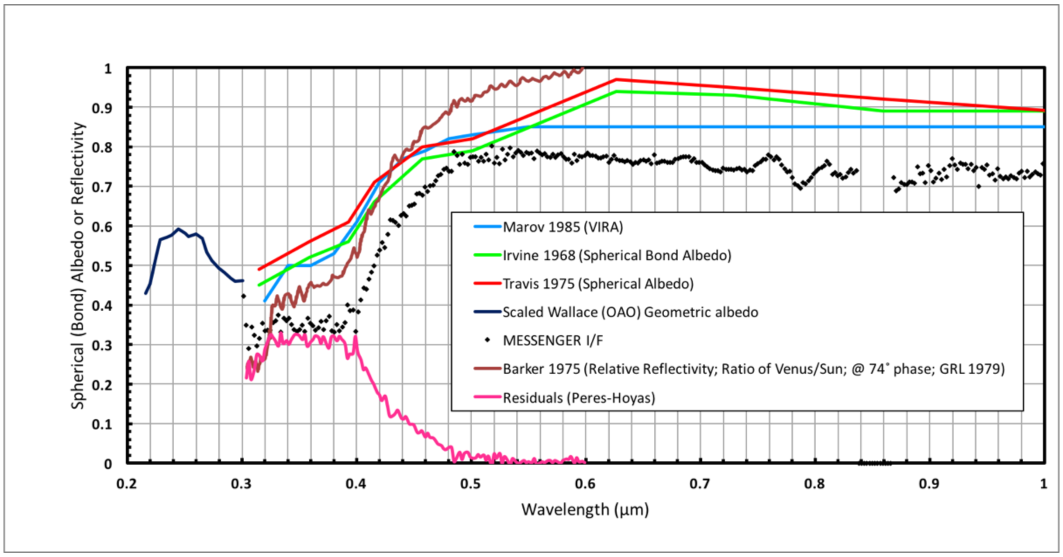


Figure 2. *Venus spectra as measured by Moroz (VIRA, 1985), Irvine (1968), Travis (1975), Wallace (scaled geometric albedo), MESSENGER, and Barker (1975), including residuals.*

Spatial Contrasts in the Ultraviolet Spectrum

From ground-based and spacecraft observations, it is widely accepted that Venus’ clouds contain micron-sized particles (Hansen & Hovenier, 1974; Knollenberg et al., 1980) consisting of sulfuric acid solutions (75-98%). In fact, all UV and blue images of Venus show small scale (10-100 km) contrasts at 270 nm (Pioneer Venus OCPP, polarimetry mode), 283 nm (Akatsuki), 365 nm (Mariner 10, Venus Monitoring Camera on Venus Express), 410 nm (Galileo), and 430 nm (MESSENGER MDIS), which evolve over time scales ranging from minutes (~50 km spatial scales) to days (~1000 km). Rapid changes in atmospheric appearances have also noted by Ross (1928), and have been observed in spacecraft images (Murray et al., 1974; Rossow et al., 1980; Titov et al., 2012).

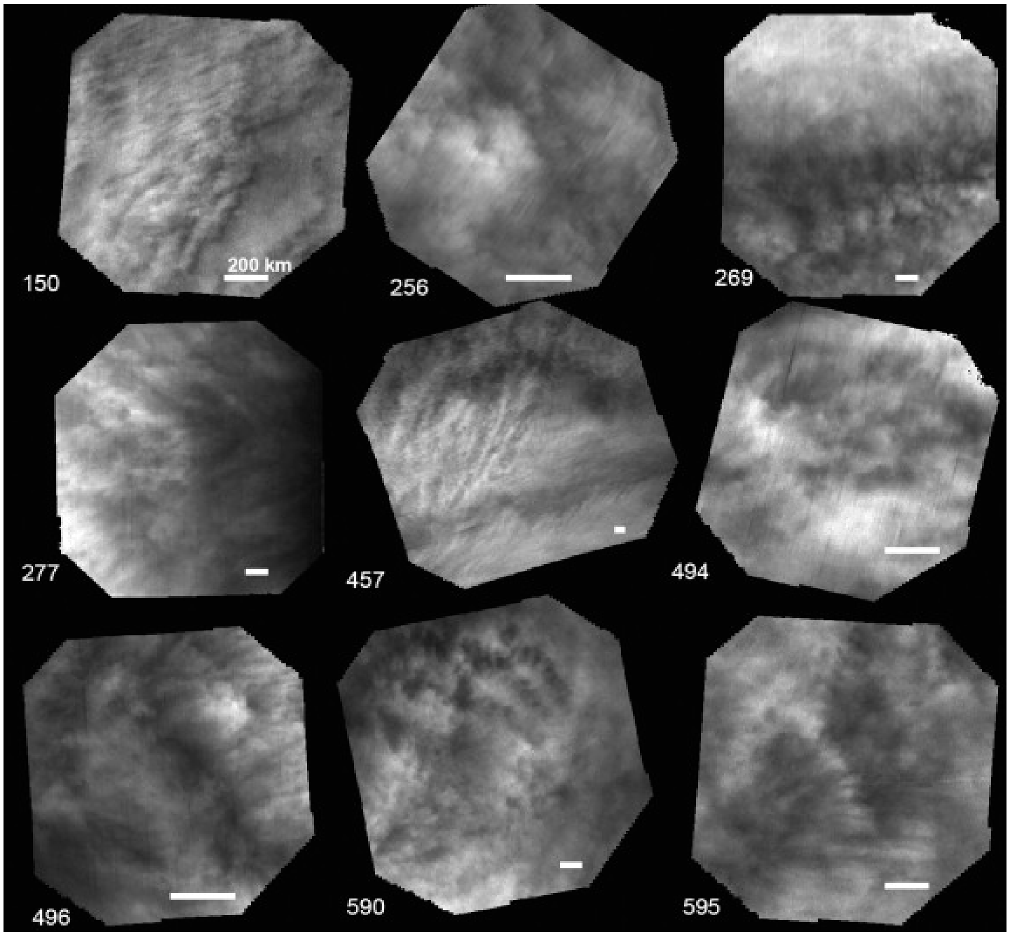
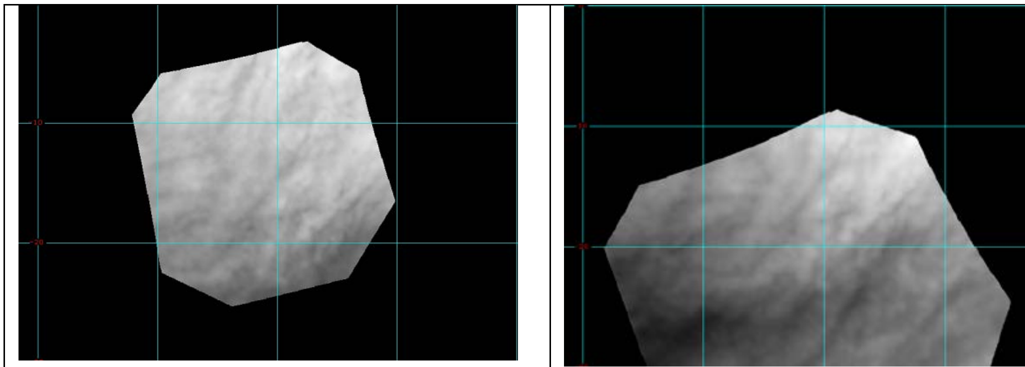


Figure 3. *Views of the equatorial region of Venus from the Venus Monitoring Camera obtained through the 365 nm filter. The numbers in the lower left of each view indicate the orbit number of Venus express (nominal period of 24 hours) while the white bar in the lower right of each image indicates 200 km scale.*

Figure 3 provides some views of the equatorial region of Venus that demonstrate the variability of the UV contrasts, over a variety of scales, as captured by the Venus Monitoring Camera (VMC) images on the Venus Express orbiter (Titov et al., 2012). Similarly, **Figure 4** provides two mapped UV images, from the Venus Monitoring Camera on Venus Express, taken only 9 minutes apart. The short-term evolution (growth and decay in terms of areal extent and contrast) of these features has been challenging to explain in terms of cloud structure, cloud top altitude differences (Ignatiev et al., 2009), and/or purely dynamical processes.



v0150-0090 18 Sep 2006 04:22:04	v0150-0091 18 Sep 2006 04:31:11

Figure 4. Rapid changes in the shape, size and magnitude of the ultraviolet contrasts are common on Venus, particularly at low latitudes where the absorption of incident solar radiation is greater. These two mapped Venus Monitoring Camera images taken through the 365 nm filter are only about 9 minutes apart. The grid lines represent latitude and longitude lines, ten degrees apart.

Absorption below 330 nm is possible by sulfur dioxide (SO_2) and sulfur monoxide (SO), which have been detected on Venus from ground based observations (Barker, 1979), spacecraft (Conway et al., 1979; Stewart et al., 1979), and entry probe measurements (Oyama et al., 1980; Surkov et al., 1978). Proposed candidates (besides SO_2) for absorption in the 200-500 nm range include fine graphite grains (Shimizu, 1977), elementary sulfur polymers (Hapke & Nelson, 1975; Toon et al., 1982; Young, 1973), octasulfur (S_8) (Schulze-Makuch & Irwin, 2006), nitric oxide (Shaya & Caldwell, 1976), croconic acid (Hartley et al., 1989), hydrated ferric chloride (Kuiper, 1969), hydrobromic acid (Sill, 1975), and chlorine (Pollack et al., 1980). Besides SO_2 and SO, others such as carbon sulfide (CS_2) (Barker, 1978; Young, 1978) and carbonyl sulfide (COS) (Bezard et al., 1990) have been detected and also absorb below 330 nm, but not between 330-600 nm (Mills et al. (2007). Esposito et al. (1983) and (Krasnopolsky, 2006) have also published discussions regarding the unknown ultraviolet absorber. The plausibility of sulfur aerosols as absorbers has been postulated (Krasnopolsky, 2016; 2017), where analysis of the (limited) data from in-situ measurements has suggested that the additional ultraviolet absorber was likely $FeCl_3$. Additionally, a sulfur oxide isomer (OSSO) has recently been proposed as an alternative UV absorber (between 320-400 nm) and a potential sulfur reservoir – however, the lifetimes of the two isomers of OSSO are very short (a few seconds) and the estimates of opacity are uncertain (Frandsen et al., 2016).

Spectroscopic measurements from VeGa 1 and VeGa 2, using a Xenon lamp, as the probes descended on the night side, established that the UV absorbers are present from the highest altitudes measureable (64 km) to the base of the clouds at 47 km (Bertaux et al., 1996). On the day side, much of the incident sunlight at UV wavelengths is absorbed at an altitude of 57 km, preventing detection of the absorber using sunlight. To date, there are very few measurements providing spatial and temporal variability of the absorbers. Spatial and temporal variability has been detected in the case of SO_2 above the cloud tops (Encrenaz et al., 2016), but the reasons or causes of the variations remain unknown. Near simultaneous Akatsuki observations of Venus at 283 and 365 nm have indicated (Lee et al., 2017) that SO_2 variations can explain some of the differences in the contrasts, but as noted earlier, there are other trace species which may also contributre to the observed variations.

Based on observations of the glory effect, $FeCl_3$ has also been proposed as a candidate (Markiewicz et al., 2014), and remains the most likely contender as a UV contrasting agent (Krasnopolsky, 2017). However, Zasova et al. (1981) note that $FeCl_3$ is not stable in the presence of sulfuric acid, presumably due to formation of $Fe_2(SO_4)_3$. As such, a continuous resupply of $FeCl_3$ would be required (presumably from the surface) to support the observed contrasts. This assessment, in turn, poses several questions regarding the mechanism of $FeCl_3$ particle transport to 50 km above the Venus surface, and the potential for $FeCl_3$ particles to act as cloud condensation nuclei (on observed timescales).

Thus, the identities of the UV absorber/s (330-600 nm) remains uncertain, and the accuracy of current cloud models do not yield adequate explanations for the lack of mixing (for the substance(s) responsible for the UV contrasts), or the spatial and temporal changes in opacity. In this absence of cohesive physical and chemical explanations, we present a discussion of Venus' clouds as a favorable habitat for life, where biological sources may serve as contributing factors to the observed spectral contrasts.

Can Biology Contribute to Venus' Spectral Signatures?

The possibility of airborne Venus life was discussed by Morowitz and Sagan (Morowitz, 1967) and followed up by Cockell (Cockell, 1999), Schulze-Makuch et al, and Shulze-Makuch and Irwin (Schulze-Makuch et al., 2004; Schulze-Makuch & Irwin, 2002; 2006). These reports introduced the premise that acid resistant terrestrial bacteria could potentially tolerate the Venus cloud environment, and metabolize through phototrophic and chemotrophic means. As is the case for any extremotolerant biology discussion, parameters such as temperatures, radiation levels, and the presence of available water serve as major limitations for habitability. However, in the context of Venus' clouds, these specific issues are likely non-limiting.

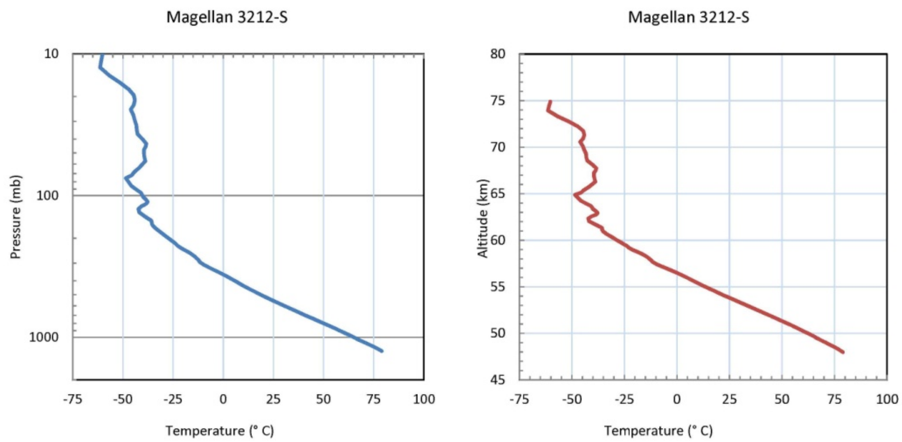


Figure 5. *Representative atmospheric temperature variation with pressure (left) and with altitude (right) in the Venus atmosphere. The profile shows Magellan radio occultation profile (Jenkins et al., 1998).*

As displayed in **Figure 5**, the bottom cloud layer at ~48-50 km possesses rather favorable conditions, with temperatures of ~60 ˚C and pressures of ~1000 mbar, or ~1 atm. Further, as described by Cockell (1999), UV radiation in the Venus' cloud layer is likely not prohibitive to life, since the UV flux in the upper levels of the atmosphere of Venus are comparable to the surface flux of Archaen Earth, when life on Earth was thought to emerge, and substantially attenuated within Venus' cloud layer due to atmospheric CO_2 and the aforementioned UV absorbers. In terms of water availability, water vapor values at altitudes of 40 km and higher are thought to vary widely from 20-50 ppm at latitudes of 60˚, to >500 ppm near the equator, with global averages suggesting mixing ratios of 40-200 ppm. However, desiccation in the Venus atmosphere may be avoidable despite these low water abundances, due to the hygroscopic nature of sulfuric acid (which would likely yield droplets or aerosols containing liquid water, even at high altitudes due to freezing point depression). Nonetheless, any inferences regarding the cloud particles, either near the cloud tops or at high altitudes, are the result of remotely sensed observations, and are not conclusive with respect to characterizing particle states as liquid or solid. However, if the Venus cloud particles are spherical, then the prevailing theory is that the droplets must be liquid (Hansen & Hovenier, 1974).

Across the cloud layers, the sulfuric acid aerosols are described in roughly three size modes ranging in diameter from ~0.4 µm (mode 1), ~2 µm (mode 2), and ~8 µm (mode 3), with a small number of particles as large as ~18 µm, as measured by the Venera missions (Knollenberg et al. (1980). For the total cloud layer (lower, middle, and upper clouds), ~70% of the columnar mass loading (~32 $mg \cdot m^{-3}$, assuming a total 12.5 km column) arises from particles in the lower clouds (~21 $mg \cdot m^{-3}$), where ~94% of this mass is associated with the mode 3 particles (~20 $mg \cdot m^{-3}$), ranging in diameter from 8.0 ± 2.5 µm. Assuming that these particles are indeed suspensions (or possibly heterogenous mixtures similar to terrestrial aerosols), then the majority of the observed UV contrasting materials and/or the major biomass are likely to be found in the lower clouds. In comparison, the middle cloud layer comprises only 24% of the total cloud columnar mass loading (assuming a 6 km column), despite the potential habitability of this region, where temperatures and pressures range from 10-50 ˚C and 400-800 mb.

For the lower cloud layer (47.5-50.5 km), particle densities are reported to be ~50 $particles \cdot cm^{-3}$ for the larger sizes (~2-8 µm diameter) and 600 $particles \cdot cm^{-3}$ for the smallest sizes (0.4 µm diameter), where in the middle and upper cloud layers (~50-70 km) the respective particle densities are 10-50 $particles \cdot cm^{-3}$ (~2-8 µm diameter) and 300-800 $particles \cdot cm^{-3}$ (~0.3-0.4 µm diameter), with the largest particle densities of ~800 $particles \cdot cm^{-3}$ (~0.4 µm diameter) being detected at the highest altitudes. Among these particle distributions, the largest masses are associated with the ~5-15 μm sized particles in the lower clouds, and ~2-15 μm particles in the middle clouds; with mass loading estimates ranging from ~0.1-100 and ~0.01-10 $mg \cdot m^{-3}$ for the lower and middle cloud regions (50.5-56.5 km), respectively, as reported by Knollenberg et al. (1980).

In comparison, the primary biological aerosols in Earth's atmosphere range in particle size from nanometer to sub-millimeter, and are composed of differing biological materials including bacteria, fungal spores, fungal hyphen fragments, pollen, plant spores, plant debris, algae, and viral particles (Fröhlich-Nowoisky et al., 2016; Morris et al., 2011). Global estimates of the total primary biological aerosols indicate $\sim 10^4$ $particles \cdot m^{-3}$, where the median diameters of particles containing cultivable bacteria are reported to be ~4 μm at continental sites, and ~2 μm at coastal sites (Després et al., 2012). Global measurements show that these bioaerosols are dominated by bacteria at $\sim 10^4$ $cells \cdot m^{-3}$ (Fröhlich-Nowoisky et al., 2016), thus amounting to a biomass of ~5 $ng \cdot m^{-3}$ when assuming a buoyant cell density of 1.041 $g \cdot cm^{-3}$ (Bakken & Olsen, 1983). However, localized measurements in the cloud-forming regions in the lower troposphere reveal much higher abundances of 8.1×10^4 $cells \cdot mL^{-1}$, or $\sim 10^{11}$ $cells \cdot m^{-3}$ (Amato et al., 2007), amounting to a theoretical cloud biomass of ~44 $mg \cdot m^{-3}$.

For Venus' lower clouds, therefore, the mass loading estimates (~0.1-100 $mg \cdot m^{-3}$) are comparable to the upper biomass value for terrestrial bioaersols (~44 $mg \cdot m^{-3}$), while the particle size regime (≤ 8 μm) opens the possibility that the clouds may similarly harbor suspensions of single cells or aggregated microbial communities. In theory, the 2 and 8 μm sized particles (modes 2 and 3) could harbor a maximum of $\sim 10^8$ and 10^{10} $cells \cdot m^{-3}$, respectively; these estimates assume spherical cloud particles, spherical microorganisms with a mean diameter of 1 µm, and particle densities of 50 particles·cm^{-3} (5x10^{7} particles·m^{-3}). Using these assumptions (including buoyant cell density), the theoretical and maximum biomass loadings for these particles amount to 0.2 and 14 mg·m^{-3}, respectively. Again, these values are comparable to the upper biomass levels of bacterial aerosols on Earth (~44 mg·m^{-3}). Moreover, when compared to Venus, these values are respectively ~6 and ~1.5-fold lower than the columnar mass loadings for the mode 2 and 3 particles (1.3 and 20 mg·m^{-3}) from the lower cloud region (when assuming a 3 km column depth), and well within the aforementioned range of total mass loading estimates. These calcuations and comparisons suggest that the mode 2 and 3 particles, from Venus' lower cloud layer, could possess sufficient mass balance to harbor water, solutes, and microorganisms.

To date, there are no in-depth studies focusing on the spectroscopy of aerosolized microorganisms or biomolecules under Venus conditions. Under terrestrial conditions, there are limited reports on the passive detection of aerosolized *Bacillus* spores using infrared spectroscopy (FT-IR), with measurements on ~10^{4}-10^{9} cells·m^{-3} providing mass extinction coefficients (at ~1100 cm^{-1}) in the range of ~720-1400 cm^{2}·g^{-1} (Ben-David, 2003; Ben-David et al., 2003; Blecka et al., 2012; Gurton, 2001). Further, turbidity (or optical density) measurements (at 540 nm) on concentrated aqueous suspensions of bacteria (~10^{15} cells·m^{-3}) provide mass extinction coefficients of ~4000 cm^{2}·g^{-1} (Spaun, 1962). Additionally, there are multiple reports on the remote sensing of microbial blooms in fresh and ocean waters, where the intense absorption and/or fluorescence properties of photosynthetic pigments (eg., chlorophyll *a* and phycocyanin) yield very large mass extinction coefficients, with ~2x10^{5} cm^{2}·g^{-1} (at ~640 nm) representing the terrestrial global average of chlorophyll *a* in the oceans (Bidigare et al., 1990; Hunter et al., 2010; Schalles, 2006).

The lower clouds of Venus exhibit comparable mass extinction coefficients ranging from ~500-5000 $cm^2 \cdot g^{-1}$, as estimated from size particle spectrometer (LCPS) measurements at 600 nm, and calculated using a density of 2 $mg \cdot cm^{-3}$, as indicated by Knollenberg and Hunten (1980). These total values suggest that Venus’ lower cloud region could harbor sufficient biomass to be characterizable and quantifiable through optical techniques. Moroever, comparison of Venus and Earth mass extinction coefficients are suggestive of the presence of high cell densities and/or appreciable concentrations of chromogenic pigments in Venus’ lower clouds (as inferred from measurements at 600 nm).

If Venus’ clouds indeed harbor biology, then these biotic materials could potentially exhibit spectral signatures that overlap with those of Venus’ clouds. For example, the observed contrasts at 270, 283, 365, 410, and 430 nm (Pioneer, Akatsuki, Galileo, and MESSENGER) are tantalizing similar to the absorption properties of terrestrial biological molecules, which have maximum wavelengths of absorption across the UV and visible spectra. Examples include nucleic acids and proteins which have respective λ_{max} values of 260 and 280 nm, where absorbances at these wavelengths often overlap, as is shown in **Figure 6A** for cellular extracts of *Escherichia coli* (*E.coli*). Typical absorbances of iron-containing proteins (which would presumably be high in abundance in an Fe-rich environment) are also shown in **Figure 6A**, with Fe-heme and iron-sulfur (Fe-S) cluster proteins displaying λ_{max} values between 350-450 nm (for the coordinated iron complex within the protein) and at ~280 nm (for the aromatic amino acids within the protein). Across the visible spectrum, many organic cofactors and biochemicals such as pterins, carotenoids, and chlorophylls also strongly absorb between 300-500 nm (**Figure 6B**), with the photosynthetic pigments additionally absorbing in the far visible and near infrared regions (**Figure 6B**).

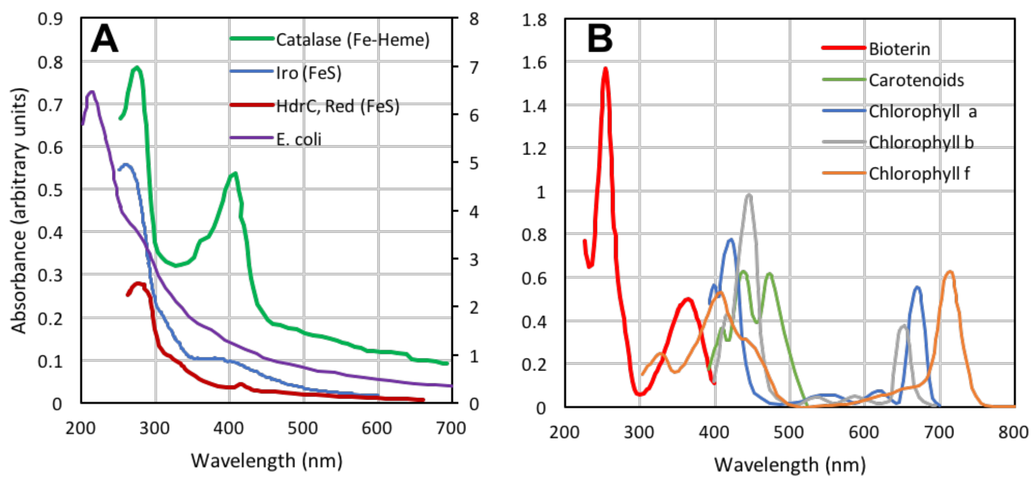


Figure 6. *Absorbance spectra for (A) whole cells of E. coli and purified iron-containing proteins of Iro and HdrC, which are FeS proteins from A. ferrooxidans, and catalase, a Fe-heme protein from Acinetobacter gyllenbergii 2P01AA; and (B) various cofactors and biochemicals, including biopterin, carotenoids, and chlorophylls a, b, and f; plots are adapted from (A) Derecho 2012 (doi:10.1089/ast.2014.1193), Ossa 2011 (doi:10.1016/j.procbio.2011.03.001), and Zeng 2007 (doi:10.1016/j.pep.2006.09.018); and (B) Airs 2014 (doi:10.1016/j.febslet.2014.08.026) and http://hyperphysics.phy-astr.gsu.edu/hbase/Biology/ligabs.html.*

As described in the preceding section, however, there are several abiotic candidates that show reasonable spectral overlap with Venus, including aerosolized elemental sulfur and ferric chloride. Comparisons of transmission spectra for these compounds and the dayside Venus albedo, as displayed in **Figures 7A** and **7B**, show that the changes in transmission > 300 nm are relatively similar. For comparative purposes, the transmission spectra of whole cells of *E. coli* and differing biological molecules are displayed in **Figure 7C**, including two iron-containing proteins and biopterin. Interestingly, the spectrum for the Iro protein (but less so for catalase) shares several similarities to the Venus albedo, as denoted by the gray dotted lines in **Figure 7**. In the context of Venus survival, these similarities could perhaps be important, as Iro is a Fe-S protein believed to be involved in iron respiration (in the acidophilic and sulfur-metabolizing bacterium, *Acidithiobacillus ferrooxidans, Zeng et al. (2007)*). While purely speculative, the lack of significant spectral similarities between the Venus and *E. coli* spectra suggest that any cloud-based microorganisms may contain high abundances of Fe-S proteins, such as Iro, in order to exhibit the observed transmission properties between 300-450 nm.

Additionally, comparisons to biopterin serve to illustrate the impact of relative abundance, as lower concentrations of this cofactor would also yield regions of spectral overlap with the observed Venus albedo. Again, in terms of speculation, this is interesting, as bacterial pterin cofactors are involved in the metabolism of sulfur compounds such as sulfite and dimethyl sulfoxide. Finally, as displayed in **Figure 8**, the UV albedo of Venus (220-300 nm) shares similarities with several UV-active biological materials (especially when considering differing relative abundances), including whole cells of *E. coli*, biopterin, carotenoids, and HdrC (an additional Fe-S protein from *A. ferrooxidans*). These preliminary comparisons demonstrate that spectral overlaps may be obtained from either abiotic or biotic sources. Hence, these spectral overlaps perhaps warrant the need for deeper investigations into possibility of biosignatures on Venus.

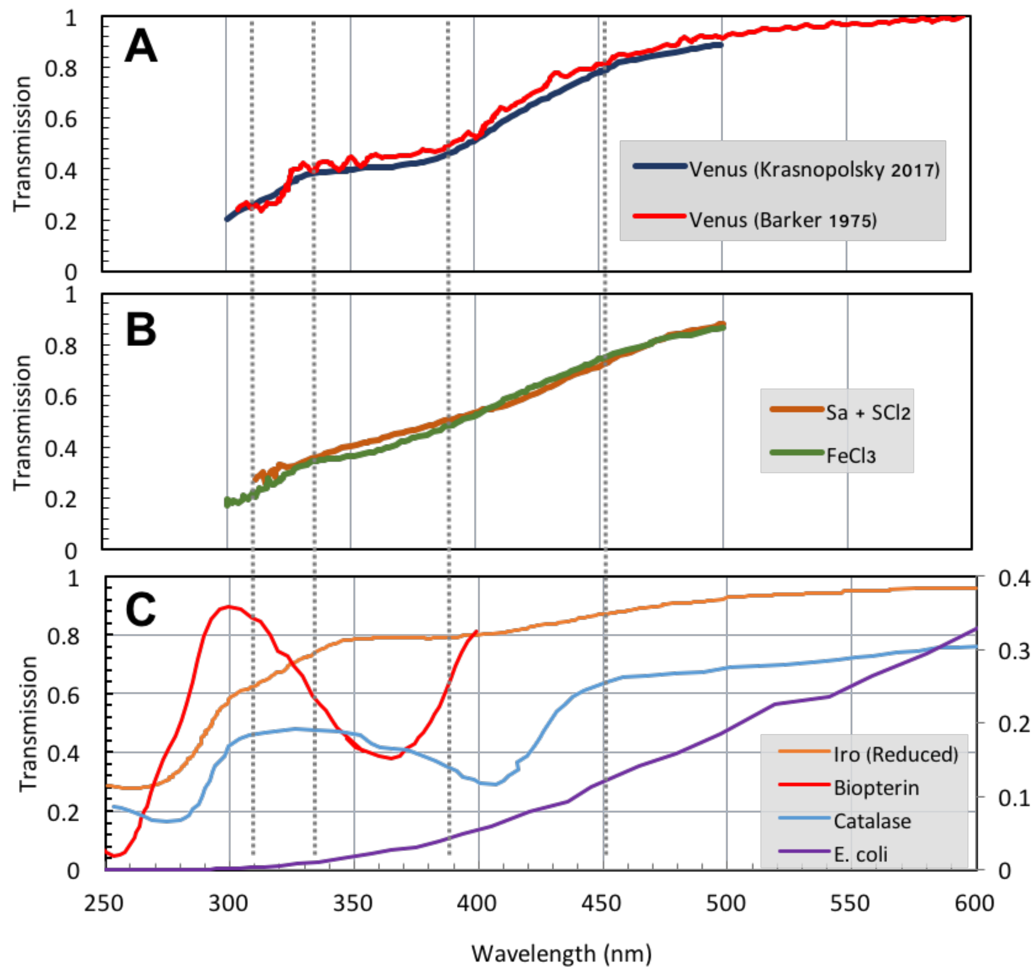


Figure 7. *Comparison of transmission spectra for (A) visible Venus albedo, as obtained from Barker 1975 (red) and Krasnopolsky 2017 (blue), and (B) aerosolized elemental sulfur (S_a) + sulfur dichloride (SCl_2) (orange) and ferric chloride ($FeCl_3$) (green), and (C) the Fe-S-containing Iro protein isolated from A. ferrooxidans (green), Fe-heme-containing catalase protein from Acinetobacter gyllenbergii 2P01AA (blue), biopterin (red), a whole cell preparation of E. coli (purple); plots adapted from (A) Barker 1975 and Krasnopolsky 2017, (B) Krasnopolsky 2017, and (C) Alupoaei 2003 (doi:10.1002/bit.20001), Derecho 2012 (doi:10.1089/ast.2014.1193), Nisshanthini 2015 (doi:10.1007/s12275-015-4138-0), and Zeng (doi:10.1016/j.pep.2006.09.018).*

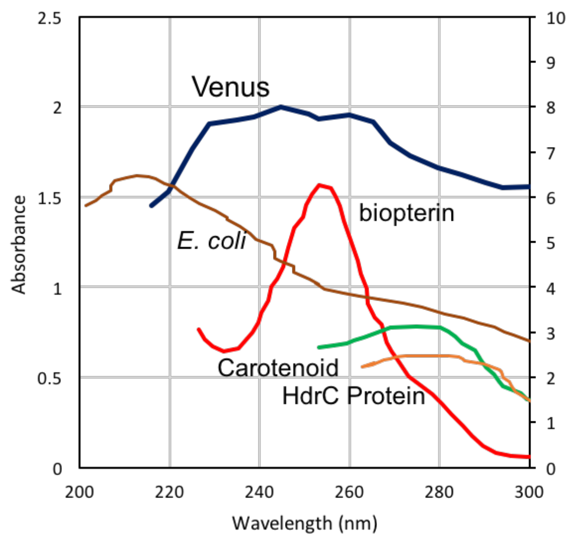


Figure 8. *Comparison of UV spectra for Venus albedo, as obtained from Wallace (scaled geometric albedo), whole cell preparation of E. coli, biopterin, carotenoids, and HdrC (and FeS protein from A. ferrooxidans); plots adapted from Alupoaei 2003 (doi:10.1002/bit.20001), Nisshanthini 2015 (doi:10.1007/s12275-015-4138-0), and Ossa 2011 (doi:10.1016/j.procbio.2011.03.001).*

Of course, these discussions must also consider the nightside opacity contrasts, which are observed vividly at 2.3 µm (**Figures 1G & 1H**). Similar to the UV contrasts, the 2.3 µm contrasts are not well understood, with potential causes including the presence of CO, and the effects of differential opacities in the upper cloud, which may impede the transmission of radiation emitted by the lower atmosphere and the surface of Venus. However, IR studies on biological and organic molecules show that reflectance and absorption at ~2.3 µm is clearly associated with C-H groups (C-H stretch) (Clark et al., 2009; Dalton et al., 2003), which is found in high abundance in lipid molecules (the primary constituent of cellular membranes). Given that the cloud layer of Venus has zonal flows which circle the planet in 4 to 6 days in the cloud layer (~50-65 km), these winds may potentially carry indigenous microorganisms around the planet, ultimately yielding contrasts on both night and day sides.

Survival in Venus' Clouds

Several terrestrial microorganisms could serve as relevant analogs for life in Venus' clouds, which are sulfuric acid-enriched, anaerobic (CO_2 dominated), and iron-rich environments. On Earth, airborne and cultivable microorganisms are routinely collected with specialized aircraft and balloons at altitudes ranging from 15-42 km (Narlikar et al., 2003; Smith et al., 2013). As mentioned, cell counts of terrestrial primary biological aerosols range from 10^4-10^{11} cells·m^{-3}, with active spectral techniques, such as laser-induced fluorescence, providing comparable measures of 6x10^7 cells·m^{-3}.

For Venus' clouds, however, any potential biomass would clearly be dependent upon available water, carbon, and other biogenic nutrients (*e.g.*, sulfur, nitrogen, phosphorous, boron, and transition metals). The phototropic reduction of atmospheric CO_2 would likely be a major source for carbon acquisition, with an attenuated UV flux within the cloud layer providing the driving energy source. Further, both phosphorus and sulfur (along with iron) have been detected by the X-ray fluorescent radiometer on VeGa 1 and VeGa 2 landers (Andreychikov, 1987), with the most abundant phosphorus compound in the lower cloud layer possibly being partially hydrated phosphoric anhydride P_2O_5+H_3PO_4 (Krasnopolsky, 2006). For water availability, the low vapor pressure in the clouds is likely offset by the aerosols composed of aqueous sulfuric acid (75-98%), where the aforementioned 2 and 8 μm spherical particles (mode 2 & 3) equate to suspension volumes of ~4 and 260 pL, respectively.

In terms of survival in sulfur-rich and low pH environments, *Acidithiobacillus ferrooxidans* serves as an exemplar terrestrial analog for life in Venus' clouds, as this bacterium thrives at extremely low pH values (pH 1–2), fixes both carbon dioxide and nitrogen gas from the atmosphere (Valdes et al., 2008), and obtains its energy for growth from the oxidation of hydrogen, ferrous iron, elemental sulfur, or partially oxidized sulfur compounds (Vera et al., 2008). This chemolithoautotrophic and acidophilic γ-proteobacterium also thrives at temperatures of 50-60 ˚C, similar to those found in the lower clouds of Venus (**Figure 3**). Moreover, under low pH and anaerobic conditions, this bacterium produces sulfuric acid, and possibly other oxidized forms of sulfur by metabolically oxidizing elemental sulfur and using Fe^{3+} as a terminal electron acceptor (Pronk et al., 1992). Members of the archaeal *Stygiolobus* genus of the Order Sulfolobales also anaerobically oxidize elemental sulfur to yield sulfuric acid under acidic conditions, and optimal growth temperatures of ~80 ˚C, and also utilize Fe^{3+} as a terminal electron acceptor (Segerer et al., 1991). Additional terrestrial analogs include green sulfur bacteria, which couple the oxidation of elemental sulfur to the anoxygenic phototrophic reduction of CO_2 (Frigaard & Dahl, 2009), and the sulfate-reducing bacteria, which couple the oxidation of low molecular weight organics and hydrogen gas to the reduction of sulfuric acid (and other oxidized forms of sulfur) to form compounds including sulfite and hydrogen sulfide (Muyzer & Stams, 2008).

Together**,** these terrestrial analogs assist in framing the biochemical potential for an iron and sulfur-centered metabolism in Venus' clouds, where oxidation of Fe^{2+} and sulfur compounds would be intrinsically coupled to the anoxic photosynthetic reduction of CO_2. As summarized in **Figure 9**, these respective iron and sulfur redox cycles could hypothetically be sustained by coupling to the redox-reactive constituents within Venus' clouds and atmosphere. For instance, nitrate reduction could additionally be coupled to the oxidation of Fe^{2+}, while completion of the Fe^{3+}/Fe^{2+} redox cycle could be afforded by coupling the reduction of Fe^{3+} to the oxidation of hydrogen, methane, and/or differing low oxidation state sulfur compounds (*e.g.*, S_x, HS^-, SO_x, H_xR_yS, & $H_xR_ySO_z$). In parallel, redox cycling between the differing sulfur oxidation states could be afforded by coupling the reduction of polyatomic sulfur compounds to the oxidation of hydrogen and/or low molecular weight organics.

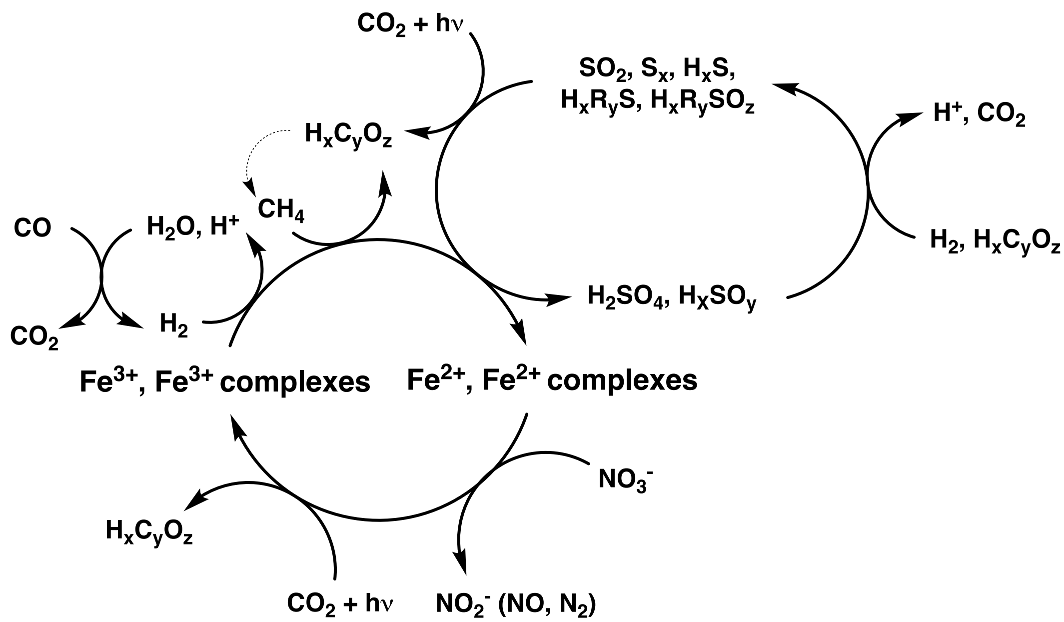


Figure 9. *Diagram of iron and sulfur-focused metabolic redox reactions that could occur in the Venus clouds, where* $Fe^{3+/2+}$ *complexes refer to inorganic and organic ligands and dotted arrows refer to possible redox cycles.*

Transport from the Surface to the Clouds

Numerical simulations have suggested that Venus had a habitable climate for at least 750 million years, with liquid water on its surface for perhaps as long as two billion years (Way et al., 2016). Presence of past liquid water was first reported from comparisons of atmospheric deuterium/hydrogen ratios between Venus and Earth (Donahue & Hodges, 1992; Donahue et al., 1982). In context, this suggests a geological timeframe that is sufficient for life to have evolved in the Venus environment, especially when the time estimates required for the evolution of life on Earth are considered (Des Marais, 1998; Lazcano & Miller, 1994; Nisbet & Sleep, 2001). As conditions on Venus' surface warmed and became increasingly inhospitable for life, surface water could have evaporated to the clouds, with multiple possible mechanisms transporting microorganisms in the atmosphere to the clouds. Ultimately, these microorganisms could have adapted to the cloud environments due to selective pressures arising from surface transport, aerosolization, limited water availability, and low pH environments.

Within the context of terrestrial biology, surface-to-atmosphere transport of microorganisms is reasonably well accepted, as is the atmospheric transport of biologically relevant elements and low molecular weight metabolites (Burrows et al., 2009; Fröhlich-Nowoisky et al., 2016; Morris et al., 2011). The movement of water, organics, and other life-essential nutrients in the upper atmosphere on Venus are likely similarly regulated by surface topography, diurnal cycles, strong storms, or a variety of other conceivable physical weathering forces. On Earth, all evidence to date indicates that airborne microbes do not remain perpetually aloft. Instead, bioaerosols are continuously swept into the atmosphere through strong convections that emanate from diverse marine and surface sources, and eventually fall out of the atmosphere through gravitational settling or precipitation.

However, for Venus, the persistent spectral contrasts indicate that any cloud-based microbial population would have to remain aloft for long periods, or be replenished on relatively fast timescales as needed. Plausible atmospheric transport mechanisms can be inferred from the VeGa 1 and VeGa 2 balloons, which occasionally experienced very strong updrafts and downdrafts (some triggered by underlying topography) at their nominal float level (~54 km). Blamont et al. (1986) reported that the typical vertical motions (up and down) encountered by the two balloons were 1 to 2 $m \cdot s^{-1}$. The recent discovery, from

Akatsuki measurements (Fukuhara et al., 2017), of stationary gravity waves at the cloud tops, which are considered to be the result of surface topography, indicate that vertical motions are possible even within the very stable cloud layer. These measurements suggest that ambient winds blowing over mountains and hills on the surface appears to trigger vertical motions, which can reach the bottom of the clouds without any impediment, and extend up to the middle cloud layer. The very stable lapse rates in the Venus clouds, due to deposition of solar energy, could also maintain airborne populations aloft for long periods. To a large extent, the atmosphere below the clouds down to the surface is close to being neutrally stable, with at least two layers with superadiabatic lapse rates, one near 4 km above the surface, and another at about 15-17 km, as based on the VeGa 2 lander data (Pioneer Venus probe sensors did not provide any data below 12 km due to an electrical problem and published values are extrapolated using an adiabatic lapse rate for pure CO_2, Seiff et al. (1995).

By extension, therefore, the observed UV contrasts of Venus are perhaps best compared to bacterial blooms, which sustain high microbial abundances and experience both temporal and spatial variability. For instance, periodic bursts in nutrients (such iron and phosphorous) can promote broad fluctuations in metabolite composition, cell aggregation, and/or cellular abundances, which ultimately result in measurable optical changes in color, opacity, and/or turbidity (Blondeau-Patissier et al., 2014; Egli et al., 2004). In Venus' clouds, such blooms may also occur on timescales that match atmospheric cycling, while changes in the metabolism of sulfur compounds (e.g., dimethyl sulfide, polyatomic sulfur compounds, and alkyl sulfoxides) could impact the degree of UV contrasts on a slower timescale. In sum, evaporation and atmospheric circulation could account for the initial and current transport of biomass from the surface, and vertically through the cloud layer, with recycling between the bottom and the top layers.

Biological material at the higher altitudes would then likely be partly or fully degraded through photochemical means, where the resulting organic products would be recycled through the cloud layer, potentially serving as carbon sources for any cloud-based biology. Such a scenario would be consistent with the conclusions of Knollenberg and Hunten (1980), that there is a source for the smaller particles in the upper cloud layer. Alternatively, large impacts could have resulted in the interplanetary exchange of rocks between Earth and Venus over the course of planetary histories, potentially seeding viable terrestrial bacteria into the Venus atmosphere.

Future Studies and Potential Challenges

Further exploration of Venus' cloud layer offers several attractive features, as the need to build lander or rover spacecraft are not necessary. Indeed, if microbes are actively metabolizing or reproducing in Earth's atmosphere, then the search for habitable zones beyond our planet should be broadened to include planetary atmospheres. As highlighted in this report, Venus' clouds are exceptional targets for astrobiology, where ground-based studies on the physical, chemical, and spectral properties (200-3000 nm) of microorganisms under Venus cloud conditions would assist in the identification of potential atmospheric biosignatures. These future studies will need to address the many sources of variation associated with the spectroscopy of bioaerosols including: (1) cell morphology (either cocci, bacilli, or spirilla); (2) cell state (vegetative or sporulated); (3) cell viability; (4) cell aggregation and biofilm formation; (5) presence of abiotic materials (e.g., dust, salts, polymer matrices); (6) state of hydration; (7) environmental and atmospheric conditions (*e.g.*, sunlight, atmospheric composition, and carrier gasses); and (8) variations based on emission source (type) and location.

In conclusion, to thoroughly investigate the habitability (or even the presence or absence of life) of the Venus clouds, a long lived aerial platform capable of observing the temporal changes in the spectral, physical, and chemical properties of the cloud layer aerosols would be ideal. Example platforms for passive and active optical strategies (e.g., IR or LIDAR based methods) include Aerobots (van den Berg et al., 2006) and VAMP, a concept being developed by Northrop Grumman Aerospace (Lee et al., 2015a), which could be deployed on a future NASA flagship mission to Venus, or on Russia's Venera-D mission currently being studied for launch (Senske et al., 2017).

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Author Disclosure Statement

No competing financial interests exist for any of the authors.

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