PRESENT STATUS OF AKATSUKI

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TAKESHI IMAMURA, & NOBUAKI ISHII

AKATSUKI PROJECT TEAM

Akatsuki (あかつき): in Japanese
Dawn: in English

Venus shot on 1st of January, 2015 in the morning from ISAS
Scientific objectives of AKATSUKI

- Understand in detail the atmospheric dynamics, by drawing 3-D view of wind fields, with multi-wavelength imaging observations (5 onboard cameras). Particular interest is the “super rotation”.

- IR2, UVI, LIR cameras are used to describe spatial and temporal variations of clouds, to understand the role of clouds in dynamics and current environment. Surface is studied for mineralogy and volcanism by IR1.

- To answer the long-time controversy of Venus lightning with an “optimized” high-speed sampling sensor LAC.

- Coordinated imaging and radio occultation measurements will tell us relationship between cloud morphology/dynamics and vertical temperature profile.
How AKATSUKI arrived at Venus

The main engine got broken during 2010 VOI due to a faulty check valve in the fuel line. Oxidizer rich and fuel poor condition resulted excessively high temperature at the orbital maneuver engine.

- The 2015 VOI-R was performed by combining 4 RCS thrusters located on the top panel (20 minutes burn).

The first-light images in orbit

- Right after the successful VOI on December 7, 2015, UVI, IR1 and LIR acquired the first images.
- The LIR thermal image is especially striking.
- IR2 imaged Venus on December 11, 2015 after the PtSi detector cooled down to low temperature (< 70 K).
Notable dates

- **VOI-R1 (DEC 7, 2015)**
  - Period: 13 days, apocenter altitude: 0.44 million km
- **VOI-R2 (DEC 20, 2015)**
  - Period: 10.5 days, apocenter altitude: 0.36 million km
- **COMMENCE OF REGULAR OBSERVATIONS (APR 1, 2016)**
- **PC1 (APR 4, 2016)**
  - Period: 10.8 days, apocenter altitude: 0.37 million km
- **SUPERIOR CONJUNCTION (JUN 7, 2016)**
  - Solar corona observation (RS)
- **ONE VENUS YEAR IN ORBIT (JUL 19, 2016)**
In the “new” orbit around Venus

**Global imaging:**
Visualize the cloud motion (wind vector) and variations of minor gases by acquiring multi-wavelength images continuously. The surface is also monitored.

**Limb observation:**
Fine-scale stratification

**Orbital period:**
10.8 days after PC1 until late 2018.

**Radio occultation:**
Radio wave propagating atmosphere is used to study atmospheric structure.

**Close-up imaging:**
Study fine-scale features including undulation. Attempt to detect lightning in the night.
On-board instruments in brief

five cameras + one ultra-stable oscillator
SCIENTIFIC RESULTS USING EACH INSTRUMENT
UVI compares SO$_2$ and “unknown” absorber

With 283-nm and 365-nm filters, UVI compares spatial distribution of albedos of SO$_2$ and “unknown” UV absorber to study the transport of SO$_2$, relation to dynamics and cloud formation.

- Total number of pairs used: 387
  periods: 2015-12-07 to 2016-08-11
- They compared albedo, which is the ‘radiance factor’ obtained by photometric correction using the Lambert and Lommel-Seeliger law.
An example of high correlation cases

2016/08/03, Pho: LLS

283 nm (12:13:53)  365 nm (12:17:29)

Dusk side (Sub S/C: 17LT)

Lee et al.

C.Coeff. = 0.960
An example of low correlation cases (I)

2016/07/02, Pho: LLS

283 nm (08:13:44) 365 nm (08:17:19)

C.Coeff. = 0.630

Afternoon side (Sub S/C: 14LT)

Dark at 283 nm & Bright at 365 nm
- Relatively less unknown UV absorber and more SO$_2$ abundances,
- or, unknown UV absorber covered by upper haze but not for SO$_2$
An example of low correlation cases (II)

2016/04/25, Pho: LLS

283 nm (13:13:40)  
S

365 nm (13:17:16)  
S

Morning side (Sub S/C: 10LT)

Bright at 283nm & Dark at 365nm
- Relatively less SO$_2$ abundance and more unknown UV absorber,
- or, SO$_2$ covered by upper haze but not for unknown UV absorber

C.Coeff. = 0.725
Both high and low correlation cases exist for the comparison between 283 and 365 nm images. In low correlation cases, we typically observe either of the following cases:

(1) dark 283 nm & bright 365 nm over afternoon side
(2) bright 283 nm & dark 365 nm over morning side

• The albedo used in these slides needs to be updated in the future study
This IR1 image at 1.01 µm demonstrates its ability to map thermal emissions from the surface. Aphrodite terra appears an E-W elongated low-temperature region, well compared to MAGELLAN altitude map.
IR2 has 5 filters

IR2 filter transmission (Half-cone angle = 15°, T = 298 K)

- H-band (1.65 μm)
- 1.735 μm
- SWPF (x0.5)
- strong CO₂ absorption
- 2.02 μm (x10)
- 2.26 μm
- 2.32 μm

Filter Transmission [%]

Wavelength [nm]
IR2 : Six-hour movies on night side

(13 AUG 2016 @ ~0.12 M km)

IR2 (1.735 µm)  IR2 (2.26 µm)

T. Satoh
Venus cloud particle properties

- Apparent diameter: 4.3"
- Area where the solar incidence angle is more than 130 degrees were used to avoid the stray light from the dayside (i.e., within circle).
Analysis procedure

- Remove emission angle dependence of intensity [based on Carlson et al., 1993]
- Calculate empirical quantity $D$ (distance from the reference line) for each pixel

$$D = \log_{10}(l'_{1.74}) - m \log_{10}(l'_{2.30}) - D_0$$
Size parameter map D

- Most important parameter determining size parameter: cloud particle size
  As size parameter is larger, cloud particle size is larger.
- The obtained size parameter map is now carefully compared with the original 1.735 \( \mu m \) and 2.26 \( \mu m \) radiance map.

Contamination From the dayside?

2 hours later
IR2 : 2.02-µm dayside images for altimetry

• Four representative phase angles ($\alpha$) are chosen to demonstrate preliminary 2.02-µm cloud-top altimetry.

• Images acquired from near apoapsis are used for two reasons:
  • To reduce the number of pixels (currently 200 x 200 pixels area is analyzed).
  • To examine as wide background as possible for image deconvolution.
Empirical point spread function (PSF)

- The night-side images suggest the PSF:
  - To have very extended skirts.
  - To have a sharp and well-defined core.

- To reproduce these two characteristics, we combine two modified Lorentzian functions: one for radial blurring and another for cross-shaped blurring.
Deconvolution of images

- To restore the intensity distribution on the disk, while reducing the loss of light to the background, images are deconvolved (Lucy’s algorithm) using an empirical PSF. Enhancing the fine cloud structure is not the primary purpose.

- As the PSF used here is not yet optimal, the disk edge is somewhat enhanced. These areas are where the plane parallel approximation is no longer valid.
Cloud models are rather simplified:

- A layer with 1.5 optical thickness aerosol over 10 km vertical extent. Each model is labeled with the altitude of the cloud optical thickness 0.9 (see figure).
- Above the cloud top is filled with tenuous haze.
- An adding-doubling code is used to compute multiply-reflected sunlight from Venus atmosphere.
- Absorption coefficients are pre-computed for each altitude layer.

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>Model A (z = 60 km)</th>
<th>Model B (z = 64 km)</th>
<th>Model C (z = 66 km)</th>
<th>Model D (z = 70 km)</th>
<th>Model E (z = 74 km)</th>
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</tr>
</tbody>
</table>

Molecules:
- CO₂ (HITRAN, first 4)
- N₂ (HITRAN)
- H₂O (HITEMP, first 4)
- HCl (HITRAN, first 4)

Wavenumber range: 4800 – 5100 cm⁻¹

Line profile: Voigt (cutoff at 120 cm⁻¹)
Comparison of the model and observation

• Every pixel in an image has:
  • Observed brightness, and
  • A set of scattering geometries (incidence angle, emission angle, and azimuthal angle).

• Observed brightness is compared with model brightness to estimate the cloud top altitude.
For all 4 phase angles, almost consistent cloud top altitudes (nearly flat from the limb to the terminator) are derived. This may be indicating that the assumed upper cloud structure is adequate.

Cloud top altitudes for polar regions vary from deeper (small $\alpha$) to higher (large $\alpha$) systematically, suggesting that the cloud structure for these regions may be somewhat inappropriate.
Cloud tracking “Day vs. night” comparison

UVI dayside (365nm)

obs 2016-07-12

55km

65-70km

IR2 nightside (2.32μm)

T. Horinouchi & S. Murakami
IR2 : Fine-resolution limb imaging
(30 OCT 2016 @ ~8240 km)

IR2
(2.02 µm)

T. Satoh, et al.
A huge bow-shaped thermal structure extending from the northern high latitudes to the southern high latitudes was found in the dayside afternoon sector. Its end-to-end distance is longer than 10,000 km, and existed in the same region for 4 days at least. Its highest and lowest temperatures are 230-231 k and 225-226 k, respectively. Filament-like small bow-shaped structures are also identified in the lower latitudes.
a strange feature we have never seen before in mid-infrared observations.

previous observations with thermal infrared wavelengths = our expectation

Subaru/ COMICS (8-12 \text{um})
[Sato et al., 2014]

Akatsuki’s LIR observation in 2010
[Taguchi et al., 2012]
• longitude of the boundary between high and low temperature regions of the bow shape at the equator: \( \lambda_B \approx 80^\circ \sim 84^\circ \)
• angular velocity of the boundary: \( \omega_B \approx 0.6 \pm 0.2 \text{ [deg/day]} \)
• rotation speed of Venus to the sun: \( \omega_R \approx -3.1 \text{ [deg/day]} \)
• the bow-shaped structure looks to be fixed not to local time but on the ground.
• Left: high-pass filtered brightness temperature obtained by LIR. Surface topography is overlaid.

• Right: high-pass filtered UV radiance at 283 nm. Circles are to show a zonal flow speed of -96 m/s at the equator.

• The zonal flow is clearly seen by displacement of the UV markings, while the bow-shaped structure stays at the same geographical position.
• A weak bow-shaped structure appeared around 200° in longitude above the eastern highland of Aphrodite terra on May 6.
• Two faint bows are identified in April but in different longitudes and local times.
Another prominent bow-shaped structures appeared in late July, lasting to the end of August. Their centers were located around 90° and 130° in longitude above the western highlands of Aphrodite Terra in the equatorial region.
Where (location) and when (local time) do these events occur?

2015-12-07-11 (Bow-shaped)

Location: West part of Aphrodite Terra
Local Time: around 16h

Projected onto local time-latitude map
Where (location) and when (local time) do these events occur?

2016-05-06 (small bow-shaped?)

Local Time: Not clear around 13h
Clear around 17h
Where (location) and when (local time) do these events occur?

2016-05-16 (filament-like feature)

Location: Thetia Mons
Local Time: Being clear around 12h
Where (location) and when (local time) do these events occur?

Remaining several weeks since 2016-07-23 (Bow-shaped)

Projected onto LT-latitude map

Location: West part of Aphrodite Terra (again)
Local Time: Being clear around 15h and after
Where (location) and when (local time) do these events occur?

2016-08-03 – 08-25 (bow-shaped)

Location: Middle-east part of Aphrodite Terra
Local Time: around 15h and after
Where (location) and when (local time) do these events occur?

2016-08-03 - 08-25 (bow-shaped)
Where (location) and when (local time) do these events occur?

2016-09-05

Location: Maat Mons (again)
Local Time: around 17h

Projected onto LT-latitude map
Same location with Same appearance
<table>
<thead>
<tr>
<th>Event date</th>
<th>Location (place name)</th>
<th>Confirmed Local time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015.12.07-12.11</td>
<td>Aphrodite Tera</td>
<td>~16h</td>
</tr>
<tr>
<td>2016.05.06</td>
<td>Maat Mons</td>
<td>~15h</td>
</tr>
<tr>
<td>2016.05.16</td>
<td>Theia Mons</td>
<td>~12h</td>
</tr>
<tr>
<td>2016.07.23 – 08.25</td>
<td>Aphrodite Tera</td>
<td>15h – 19h</td>
</tr>
<tr>
<td>2016.09.05</td>
<td>Maat Mons</td>
<td>~17h</td>
</tr>
</tbody>
</table>

• These events mainly occurred above huge mountains in low latitudes

• Periodical: Same location has same feature-events at same local-time

=> Daily events of Venus

• The features became clearer in evening region.
- Geopotential forcing: 60 m²s⁻² at (180°, 0°), e-folding distance of 6°
- Grid: 3° × 3°
- Altitude range: 10 – 96 km, 100 layers

Simulated by T. Imamura
RS: vertical scan of atmosphere

T. Imamura & H. Ando

Dawn (LT = 4.7–5.5)

Dusk (LT = 16.2–17.5)
LAC: Now ready to start lightning observation

- The instrument is quite healthy, and HV level almost reach nominal level.
- Lightning has not detected yet, but the sensitivity will be double to the next observation.

<table>
<thead>
<tr>
<th>FOV</th>
<th>16 × 16 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens</td>
<td>Single 25 mm diameter</td>
</tr>
<tr>
<td>Sensor</td>
<td>8 × 8 multi-anode SiAPD</td>
</tr>
<tr>
<td>Pixel size</td>
<td>2 mm × 2 mm</td>
</tr>
<tr>
<td>Bit rate</td>
<td>10 bit/pixel for lightning</td>
</tr>
<tr>
<td>Sampling time</td>
<td>32 μsec sampling</td>
</tr>
</tbody>
</table>

LAC Observation Schedule

2016/08/02 (not detected)
- 2.5 min. exposure, HV = 270 V

2016/11/09 (not detected)
- 20 min. exposure, HV = 280 V

2016-11-20 (under analysis)
- 22 min. exposure, HV = 290 V

2016-12-01
- 11 min. exposure, HV = 300 V (nominal)

…

Cosmic ray has detected.

Coming soon

Y. Takahashi, M. Imai, & M. Sato
Summary

• AKATSUKI was successfully inserted in Venus orbit, and on-board science instruments are acquiring high-quality Venus data.

• Although the orbit is more elongated than envisioned, benefit of being in the equatorial plane to study dynamics is obvious.

• The science team expects to achieve all success criteria in the nominal mission period (the end of March 2018).