An optical flash on Venus detected by the AKATSUKI spacecraft

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Detection of lightning discharges on Venus has been attempted using both radio waves and optical methods for over 40 years. For optical observations, claims of lightning detection were controversial due to the lack of time resolution of optical emissions that is needed to separate lightning from artificial or natural noise. Here we show the first high-time-resolution light curve of a transient optical phenomenon observed by the Lightning and Airglow Camera (LAC), a dedicated instrument on the Venus orbiter Akatsuki. The observed transient was 10 times brighter than a typical terrestrial lightning flash and had a duration of a few hundred milliseconds, whereas that of typical Earth lightning is only a millisecond. These characteristics are not typical, but are well within the variability of Earth lightning. An origin as a bolide flare cannot be excluded, but considering the expected occurrence frequency of meteoroids at Venus, is improbable. The low flash rate and long duration determined by the Akatsuki observation are not inconsistent with non-detection of lightning radio waves by the Cassini spacecraft.

Evidence of lightning on Venus has been sought for more than 40 years using both radio waves and optical methodss[1-10]. However, lack of consensus on its occurrence is due to an absence of combined observations, limited observation periods, and poor performance of instruments which are not optimized for lightning detection. Most of the optical records of lightning lack high temporal resolution, making it difficult to discriminate lightning signals from natural or instrumental artifacts. The Lightning and Airglow Camera (LAC) onboard Venus orbiter, Akatsuki, is the first optical sensor designed specifically for lightning flash measurement on planets other than the Earth[11]. The unique performance of the LAC compared to other equipment used in the previous exploration of Venus is the combination of a high-speed sampling at 20 kHz with a spatial discrimination using a 4 x 8 pixel Avalanche Photo Diode (APD) detector array and high sensitivity using a high-voltage (HV) bias of up to 300 V. Data are captured for an individual 2° x 2° pixel for each event by triggered recording. These features let us distinguish a natural optical lightning flash from other transient signals, such as electrical noise and cosmic rays (as on comparable instruments flown on Earth satellites, e.g. FORTE[12], GLM or GLIMS). The field-of-view (FOV) of LAC is 8 x 16 degrees, covering a typical footprint >1000km across. We selected a narrow band filter for the OI 777 nm line to detect lightning flashes on Venus, which is expected to be the most prominent emission in the CO2-dominant atmosphere based on laboratory experiments[13].

Akatsuki was launched in May 2010 and inserted into Venus orbit in December 2015, circling Venus with an orbital period of 10 days[14]. We started the lightning survey with LAC in 2016 and carried out 57 observation sessions totalling 22 hours when Akatsuki was in the shadow of the planet, and the accumulated coverage reached 110.3 x 10^6 km^2-hour by the end of September 2020. We used two sets of triggering parameters optimized for different types of light curves, that is, typical cloud-to-ground lightning on Earth (time constant: order of milliseconds) and sprites with slower changes in luminosity (time constant: order of 10s of milliseconds). No events resembling lightning flashes were observed in the first three years of operation[15].

On March 1st, 2020, LAC recorded for the first time an event showing slow increase and decrease of intensity with a time constant of few 10s of milliseconds (Figure 1a). LAC has, however, detected 466 cosmic ray events over 19.1 hours. The "signal" of a cosmic ray strike shows an instantaneous jump in intensity within a LAC sampling interval of 50 μs and a decrease with 1/e-folding time of the APD circuit (0.8 ms) as shown in Figure 1b. Such a 'light-curve' is very different from optical emissions of lightning or a bolide flash. At the time of the detection of the optical phenomenon, Akatsuki was located at a distance of 3,300 km from Venus' surface, and the center of FOV of the pixel that sensed the optical flash was pointed at (-31.8° latitude, 35.3° longitude) as indicated in Figure 2a, which corresponds to 00:58:47 Local time, together with total FOV of 4 x 8 pixels of LAC in Figure 2b. The estimated peak intensity and total photon numbers are 4.5 times and 11 times larger than those of typical lightning on the Earth with an optical energy of 10^6 [J] under the cloud, respectively, meaning the time-integrated optical energy of the detected event is 1.1x 10^7 [J]. The duration was 220-230 ms, and the FWHM (Full Width at Half Maximum) 30-50 ms.

Though the duration of the present event is much longer than that of a typical terrestrial lightning flashes observed from Earth orbit. However, it is within the range of variation of those measured by GLIMS onboard the International Space Station[16], showing most of the cloud flashes have FWHM of few ms. Also, though the intensity and total photon numbers are somewhat larger than typical for the Earth, they are similarly well inside the observed range. The total optical energy is 1/9 of the lowest flash observed at Venus with a ground telescope[6], namely, 1x10^8 [J]. The occurrence frequency indicated by our survey, one per ~100 M km^2 hour, is equivalent to that of the ground telescope observation[6]. Figure 2c indicates the location of the present event on the cloud map composited from images taken at 365 nm by Ultra Violet Imager (UVI) onboard Akatsuki in previous 4 days. The flash seems to happen on a dark streak at latitude of about 30 degrees extending in zonal direction, which compose a main part of large scale "Y" structure.

A bolide is an alternative explanation for the flash, which would have an estimated equivalent observed magnitude at Venus of -17.0. The probability of observing such a rare bolide from Venus orbit is estimated to be 0.05-4 percent for the 4 year observation by LAC based on the time-integrated photon numbers. If we consider the fact that the duration of the present event, ~200 ms, is much shorter than that of typical bright terrestrial bolides lasting a few seconds, this scenario seems even less probable. According to Figure 2 the location of the optical event is not near any prominent topographic or volcanic feature, so there seems no direct connection between the present event and volcanic activity. We consider the signal unlikely to be an instrumental artifact as we have detected no similar waveforms for 4 years and have confirmed normal LAC operation 7 times after the detection of the present event, recording LAC output signals by forced triggering in the same high voltage condition.

Optical and radio/magnetic transients detected at Venus, were proposed to be due to lightning[10]. Most optical surveys (e.g. Pioneer Venus and Venus Express[9]) have indicated no flashes. Of note is that the first claimed optical detection by spacecraft, that of Venera-9[(2)], reported multiple flashes over a 70 s period with a duration of 250 ms and optical energy of ~3×10^7 J, individually not too different from the flash we report here. Those detections were in the first minutes of operation of the (non-imaging) Venera spectrometer instrument, and it is suggested that tumbling debris shed from the spacecraft might have been responsible for some near-field reflection of sunlight[10]. Scattered light of this sort can likely be excluded for this Akatsuki observation, since only a single pixel of the LAC was triggered, and that only once. We did observe scattered light early in the Akatsuki mission when an observation was made near the illuminated limb of Venus, and this had a near-constant intensity, quite different from the brief transient we observed in this paper.

The optical detection in ground-based telescopic data[6] had flashes that must have been less than ~50 ms in duration, since these flashes did not persist from one frame to the next in an imaging sequence obtained at 18.8 frames per second. Those flashes (of which 7 were observed in ~4 hours of observation over 5 nights) had higher optical energies (10^8 – 2×10^9 J) than that reported here.

It may be noted that the VLF (radio) signatures identified by Ksanfomality in Venera 13 & 14 data as lightning sferics were persistent, with many pulses per minute for a period of tens of minutes. Similarly the Venera-9 detections spanned 70 s[(2)]. If the phenomena responsible for these effects were also responsible for the flash we detected, it is puzzling that we observed only a single event. On the other hand, such low occurrence rate is not inconsistent with non-detection of radio waves caused by lightning by the Cassini spacecraft.

We conclude that the present event is most likely a lightning flash in Venus' atmosphere, though the possibility of an unusual bolide is not zero. It represents the first reliable optical observation from orbit, and indicates a low flash rate in the clouds. This low flash rate may imply the result of inefficient charge separation processes, due to the low mass loading and particle collision rates in the clouds[17, 18] and the lack of frequent deep convective motions, which are necessary conditions for generating electric fields that can surpass the local gas breakdown value for the CO_2 – dominated atmosphere of the planet. If the event was a bolide, it is nonetheless remarkable since no such event has previously been detected.

(1561 words)

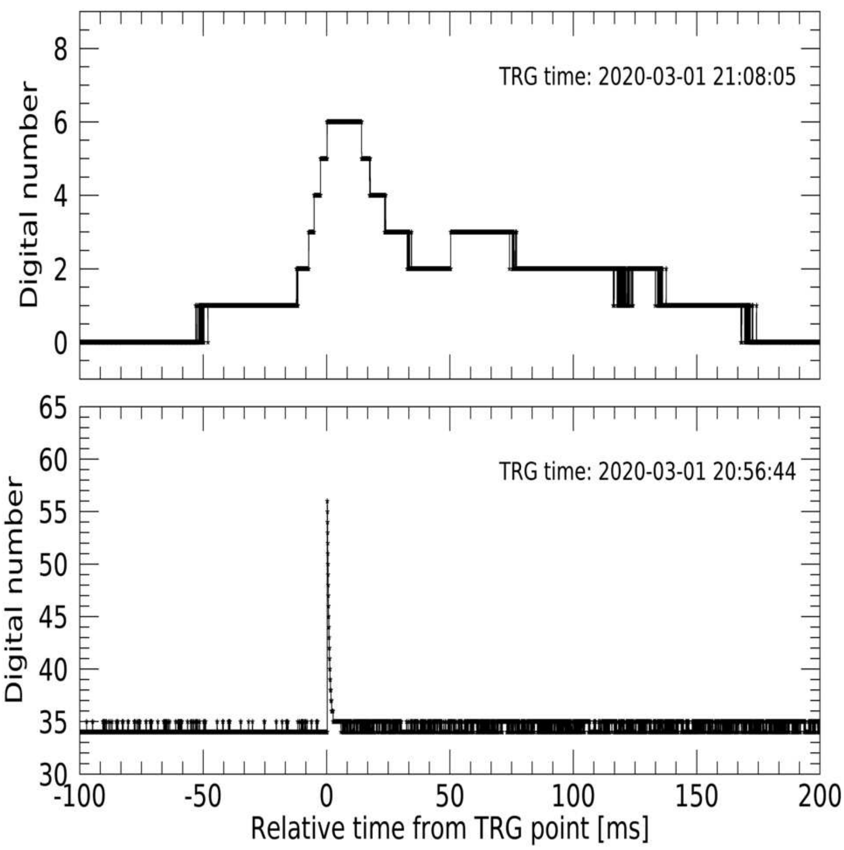

Figure 1 | a (top): Light curve recorded on March 1, 2020. The maximum intensity corresponds to 4.5 times larger than those of typical lightning on the Earth ,and the time is given in ms relative to the trigger (TRG) point. **b (bottom): A typical time variation of a cosmic-ray event.** The intensity reaches the maximum with one sampling interval of 50 µs from the background level and decreases with 1/e-folding time of APD circuit (0.8 ms).

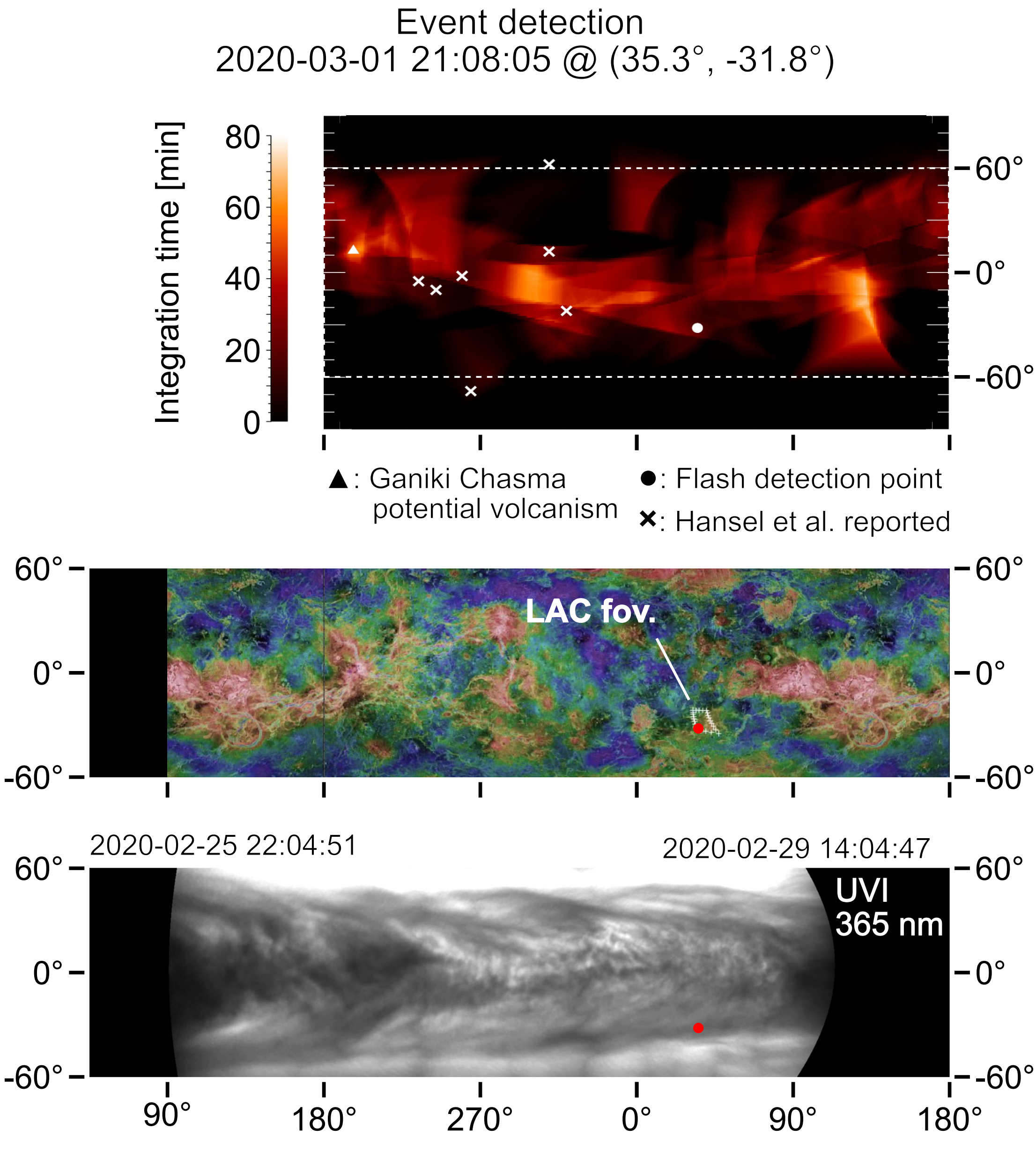

Figure 2 | a (top): **Map of integrated time period of observation. Color code expresses the total observation time integrated in the period from August 2016 - March 2021. The white circle denotes the location of the detected flash. White crosses and triangle show flash locations reported by Hansel et al. [1995] and the Gniki Chasma potential volcanism, respectively. b (middle): LAC Filed of View (FOV) projected onto Venus Global Map.**

Total **FOV** of LAC for lightning measurement (4 x 8 pixels) projected on **Venus Magellan Global C3-MDIR Colorized Topographic Mosaic** 6600m v1 from NASA web page. The red circle denotes the location of the detected flash. **c (bottom): Composite cloud map of ultraviolet (365 nm) image and location of the optical flash.** Images taken by UVI onboard Akastuki in the period of February 25 – 29, 2020, were used to make a composite cloud map, assuming the zonal wind velocity of e100 m/s. The optical flash is located (red circle) on the dark streak lying at latitude of about -30 degree.

Data:

Akatsuki data, once released after peer review, are archived online (https://www.darts.isas.jaxa.jp/planet/project/akatsuki/index.html.en).

Author Contributions:

Yukihiro Takahashi: LAC principal investigator
Masataka Imai: Data analysis
Mitsuteru Sato: Observation planning
Ralph Lorenz: Science discussion

Masato Nakamura: Project and observation planning
Takehiko Satoh: Observation planning
Atsushi Yamazaki: Akatsuki and LAC operation planning
Takao Sato: Akatsuki and LAC operation planning
Takeshi Imamura: Scientific discussion

Yoav Yair: Determining science target and scientific discussion
Karen Aplin: Determining science target and scientific discussion
Georg Fischer: Determining science target and scientific discussion

Jun Yoshida: LAC development

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Methods

(appeared only for electronic version)

[Sensitivity calibration]

From calibration data of CH13 (corresponding channel) in the laboratory before launch, 1 digit (DN) = 10^4 [R] @HV=340V @T=+2°C. The photon number into LAC at 10^4 [R] (A=5 [cm2], Ω=1.2 x 10^{-3} [str]) is: 10^4 [R]/(4π) x 10^6 x A[cm^2] x Ω[str] = 4.8 x 10^6 [ph/sec/digit]. The time of detection was during the shutdown process of LAC and the HV of APD was 208 V, yielding lower sensitivity than for the nominal operation with 300 V. Considering the high-voltage to APD sensor and its sensor temperature, the sensitivity at the event detection is expected to be 23 times lower than the calibrated value. The maximum value (6 digit @HV=208 V @T=+18° C) of the record corresponds to: 4.8 x 10^6 [ph/sec] x 6 x 23 = 0.66 x 10^9 [ph/sec/6digit].

[Assessment of lightning flash duration]

Consideration of the geometry of the Venus cloud deck (50 km above the surface) shows that the spread of arrival times due to the different propagation paths of scattered light from an impulsive release of photons near the surface would only be about 1-2 milliseconds. Thus the source pulse of light must itself have been around 200 ms in duration and no useful constraint can be derived on the flash depth. The long emission timescale might be more consistent with an upper-atmospheric source or a bolide, than a conventional 'earth-like' flash.

[Estimation of magnitude assuming the event was caused by a bolide]

Here we consider a meteor which shows a magnitude of Jupiter (-2.4) at distance of 100 km (to the ground). Since the solar radiance at 777 nm at the Earth is 1.07 [W/m^2/nm], it will be 1.07 x $(1/5.2)^2$ = 0.040 [W/m^2/nm] at Jupiter. Assuming the reflectance of Jupiter at 777 nm is 0.40, the radiance from Jupiter will be 0.040 x 0.40 = 1.6 x 10^{-2} [W/m^2/nm]. Using hv= 2.5 x 10^{-19} @777nm, this can be expressed in Rayleighs"[R]"as 6.4 x 10^6 [R/nm] = 0. 64 M [R/0.1 nm]. Then, the photon number becomes I [R]/4π x 10^6 x Ω x A = (0.64x10^6) / 4π x 10^6 x (4 x10^{-8}) x 5 = 1.0 x 10^4 [ph/sec/0.1 nm]. Since the bandwidth (FWHM) of LAC is 9 nm, the photon number will be 0.9 x10^6 [ph/sec/9 nm]. If we observe this meteor at distance of 3,300 km, this number will be 0.9 x 10^3 [ph/sec/ 9nm] @3,300 km. The observed peak (0.66 x 10^9 [ph/sec/6 digit] is (0.66 x 10^9) / (0.9 x 10^3) =0.7 x 10^6 times (=14.6 mag.) brighter than Jupiter (-2.4), namely, a magnitude of -17.0. This value is 50 times brighter than the full-moon observed on the Earth.

[Estimation of bolide frequency]

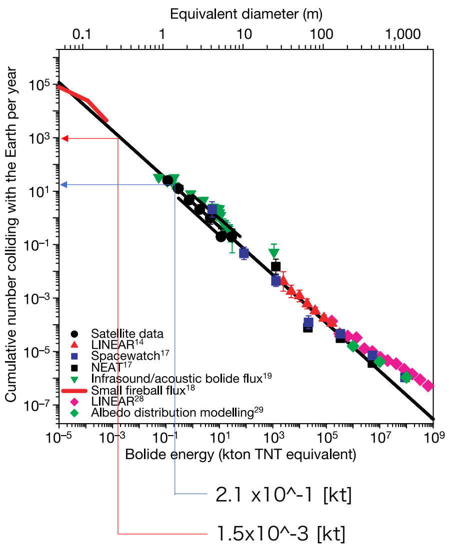
The observed peak value of 0.66 x 10^9 [ph/sec/6 digit] is equivalent to 4.5 x 10^7 [J/sec/6 digit] at the light source. Since emission energy at 777 nm with bandwidth of 9 nm is 1/140 of the total blackbody energy at 6000 K, the total optical energy will be 6.3 x 10^9 [J/sec/6 digit]. We confirmed that even if we take a bolide spectrum reported by a previous study, which is different from blackbody, the ratio contributing to 777 nm with bandwidth of 9 nm is almost the same as for blackbody radiation.

If we use, TNT unit 1 kt = 4.2 x10^{12} [J],

6.3 x 10^9 [J/sec/6 digit] = 1.5 x 10^{-3} [kt/sec/6 digit]

Considering the duration of ~100 ms of the event, the time-integrated optical energy will be 1.5x10^{-4} [kt].

The estimations of the ratio between optical and source (kinetic) energy by previous studies have a wide range. Brown et al. (2002) indicated ~10 percent while Popova and Nemtchinov [1996] shows 3-5 percent and Subasinghe et al. (2017) introduced 0.7 percent in their review. Taking into account this variation, we assume 0.7-10 percent here, resulting in a source energy range of 1.5x10^{-3} [kt] - 2.1x10^{-1} [kt]. According to Brown et al. (2002), cumulative numbers colliding with the Earth per year are 1000 for 1.5x10^{-3} [kt] and 20 for 2.1x10^{-1} [kt], respectively (from the figure below, modified from Figure 4 of Brown et al., 2002).



Global area multiplied by one year is 4.44 x 10^{12} [km^2-hr].

If cumulative number is 1000, the possibility of bolide detection by LAC in 4 year observation, namely, 10^8 [/km^2-hr], will be:

1000/(4.44 x 10^{12} [/km^2-hr]) = 1000/(4.44 x10^4 x10^8) [/km^2-hr]

$= 225 \times 10^{-12} = 2.25 \times 10^{-10}$ [/km^2-hr]

1000/(4.44 x10^4) = 0.0225=2.25%

If cumulative number is 20, the possibility will be:

$20/4.44 \times 10^{12}$ [/km^2-hr] $= 20/(4.44 \times 10^4 \times 10^8)$ [/km^2-hr]

$= 4.5 \times 10^{-12}$ [/km^2-hr]

$20/(4.44 \times 10^4) = 0.00045 = 0.045\%$

According to the model calculation by Ito and Malhotra [2006], the meteorite collision probability with Venus will be 1.1-1.8 times larger than that with the Earth (their Table 1. See below). Then the probability of 2.25 % with the Earth will be in the rage of 2.48 – 4.05 % with Venus, while 0.045 % will be 0.050 – 0.081 %.

Table 1

The number of test particles N_{tp}, osculating orbital elements $(a, e, I, \omega, \Omega, l)$ of each disruption center, ejection velocity v_0, and the collision probability of asteroids that hit the Sun and planets in our numerical integrations

Case	(1)	(2)	(3)	(4)	(5)	(6)	(7)
N_{tp}	2961	2962	2961	2967	2967	2962	2976
a (AU)	2.05	2.05	2.05	2.05	2.15	2.08	2.15
e	0.05	0.10	0.20	0.10	0.10	0.15	0.20
I (deg)	1.43	2.87	5.73	2.87	2.87	4.30	5.73
ω (deg)	330.1	181.3	206.5	311.3	81.3	35.9	351.2
Ω (deg)	149.8	103.7	192.7	114.7	121.0	103.7	235.8
l (deg)	55.5	102.6	56.0	97.9	205.4	66.5	46.5
v_0 (km/s)	0.2	0.2	0.2	0.8	0.1	0.1	0.2
Sun (%)	66.0	71.6	73.1	47.3	52.8	75.4	65.5
Mercury (%)	1.01	0.68	1.38	0.57	0.37	0.84	0.97
Venus (%)	6.11	5.06	4.56	3.24	2.90	5.00	3.83
Earth (%)	4.42	3.17	2.57	2.90	2.33	3.24	2.96
Mars (%)	0.71	0.64	0.54	0.88	0.94	0.20	0.94
Jupiter (%)	0.91	0.57	0.27	0.61	0.30	0.61	0.94
Saturn (%)	0.03	0.03	0	0	0.03	0.07	0
>100 AU (%)	14.1	13.0	11.6	9.30	10.8	12.7	15.8
Survivors (%)	5.44	4.02	4.66	34.1	28.4	0.71	8.27

The fraction of particles that went beyond 100 AU and that of the particles that have survived over 100 million years are also shown. No collisions with Neptune or Uranus were observed in our simulations.

Considering the discussions above, the possibility of bolide detection by LAC in the 4 year observation period will be 0.05 - 4 %, which correspond to one event detection in 100 - 8,000 years.

If we take into account that the event shows short duration (few 100s ms) compared to typical bolide (few seconds), the detection probability of the event we observed will be even much smaller than 0.05 - 4 %.

The US government satellite surveillance of optical flashes has yielded a record (https://cneos.jpl.nasa.gov/fireballs/) of 847 bolide flashes in the period April 1988 – November 2020 (32 years), with optical energies of 2×10^{10} J to 3.7×10^{14} J, and calculated bolide kinetic energies of 0.073 kT TNT equivalent to 440 kT (the Chelyabinsk superbolide of 2013).

Thus 0.073 kT events occur at a rate of roughly 30/year globally. A similar value is found in the smaller set of satellite data in Brown et al. (2002), and lies on a single power law function ($\log_{10} N = 0.57 - 0.90 \log_{10} E$, with N the number of events per year, with cumulative energy >E in kT) which connects small fireballs (0.001 kT) to the observed Near-Earth asteroid population and expected frequency of impact events >1 GT.

Nemtchinov et al. (1997, their Figure 3 and eq.16) indicates a largely model-based luminous efficiency of approximately 0.06 for radiated energies of ~0.01 kT. A suite of satellite-observed entry events calibrated against infrasound and other energy measures by Brown et al. (2002) suggests an efficiency of 0.1 at this scale.

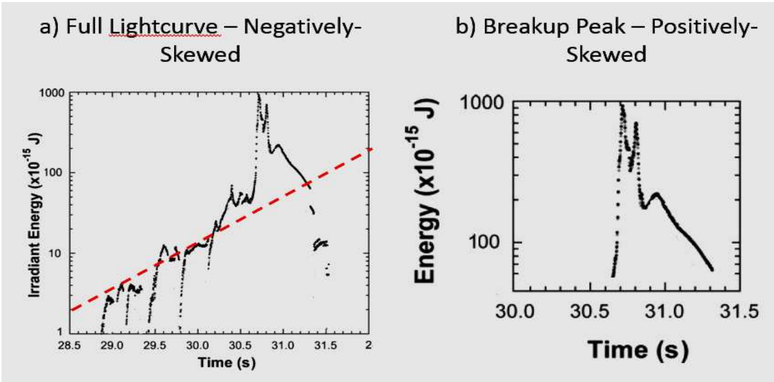
[Assessment of shape of bolide lightcurves]

The light curve we observed is positively-skewed (i.e. the long tail is towards the right, after the peak). A nonfragmenting bolide, on the other hand, has an energy deposition profile (and thus, lightcurve) that is negatively skewed, with its peak towards the end of the event. This is because a bolide entering an atmosphere from above encounters air density that increases exponentially with depth. A survey of lightcurves obtained by the GLM (Jenniskens et al., 2018) suggests that the majority of bolide lightcurves are negatively skewed.

The initial growth of intensity should be exponential with a timescale that is the same for all bolides at a given planet, namely ~H/Vsin(gamma), where H is the atmospheric density scale height (~10 km), V the entry velocity (11-30 km/s typical) and gamma the entry angle (most probably 45 degrees, but sin(gamma) cannot be more than 1.0 in any case). So a bolide's onset is almost always going to have a ramp-up with a timescale of the order of 10/(20*0.7) ~ 0.7 seconds. Only an improbably fast would ramp up in the ~30 ms we observed.

However, it is possible that we are not observing the full lightcurve of an integral body, but rather only the peak flashes of a disintegrating bolide which is overall small enough that the initial entry with a ~1s ramp-up is invisibly faint. Since entirely arbitrary breakup histories can be posited due to the stochastic nature of fracture, any lightcurve can be theoretically generated. Many of the lightcurves in Jenniskens et al. (2018) have multiple peaks due to breakup events, and the individual peaks may be positively skewed (e.g. figure below). If the onset of the lightcurve is due to a breakup event, then its ramp rate is not constrained by speed/scale height considerations above. The sharp peak in the event shown has a width of <100 ms.

Thus, the shape of the lightcurve we observed at Venus does not exclude a bolide origin, but requires an even larger and thus less probable bolide.



GLM Lightcurve of a 0.33 kT impact energy (1.1×10^{11} J) bolide on December 29, 2017 over the Atlantic Ocean, adapted from Jenniskens et al. (2018). (a) The full lightcurve is negatively-skewed. On a logarithmic y-axis the exponential growth appears as a straight line – the dashed line is a 100-fold increase in 3.5s, or an e-folding timescale of 0.76s.

If the flash is due to bolide breakup, it must happen at an altitude where the atmospheric density is less than r

where the dynamic pressure ~$0.5rV^2$ < s, and s is strength of meteoroid (typically 40 MPa)

Since V~20,000 m/s, it follows that r < 0.2 kg/m3. Equating the column mass of the atmosphere (scale height H) with that of bolide diameter d and meteoroid density r_m we have $rH=dr_m$. Thus d=1m, and mass ~2000 kg for V~20,000 m/s, KE = $0.5mV^2 = 4 \times 10^{11}$ J (0.1 kT).

Lightcurve is compatible with breakup, but for very rare event, <<1% probability.

It is of note that several bolide flashes have been detected on Jupiter by amateur astronomers (e.g. Hueso et al., 2013, 2018). These flashes were ~1-2 s in duration.

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Figures

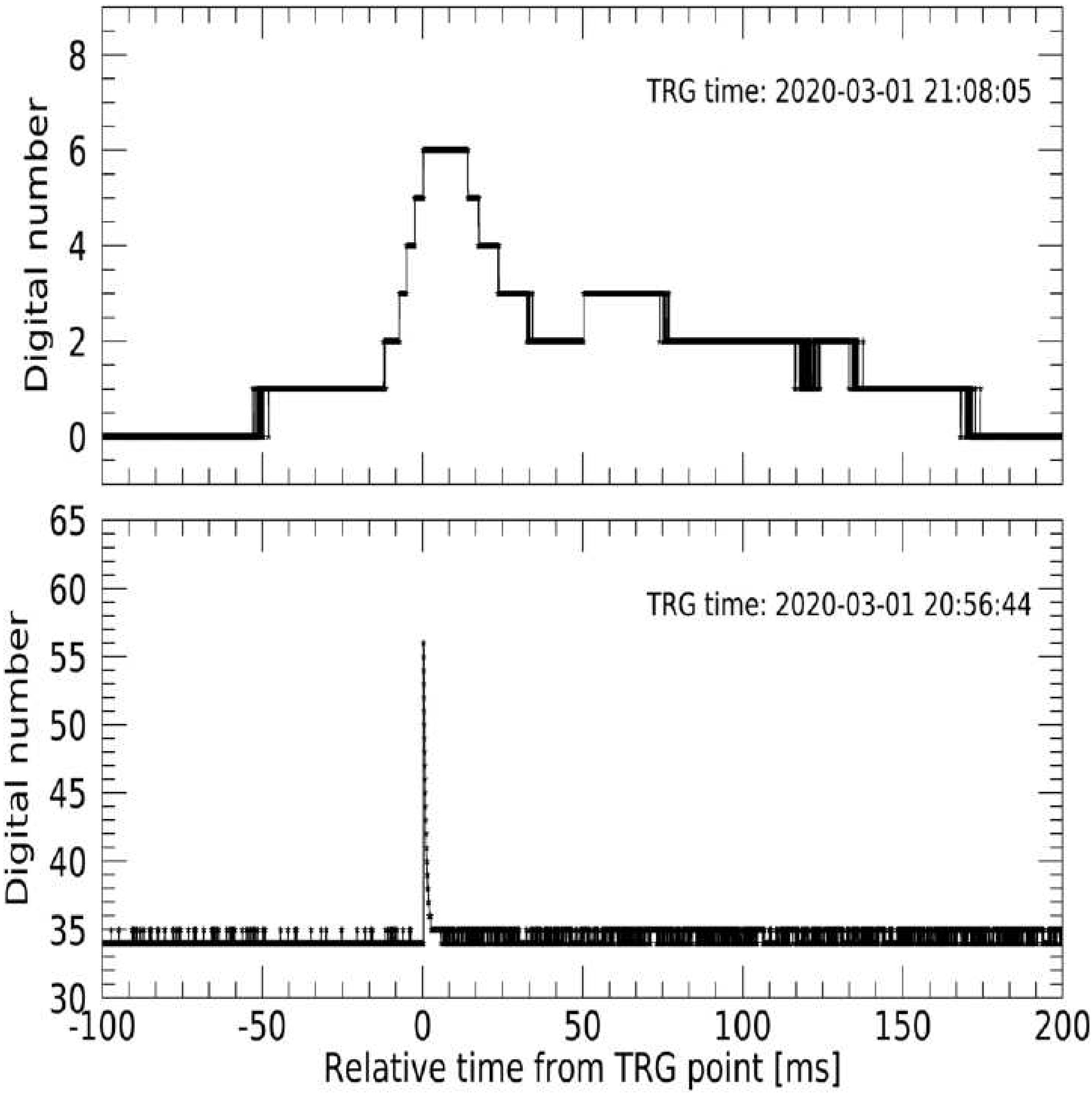

Figure 1

a (top): Light curve recorded on March 1, 2020. The maximum intensity corresponds to 4.5 times larger than those of typical lightning on the Earth ,and the time is given in ms relative to the trigger (TRG) point. b (bottom): A typical time variation of a cosmic-ray event. The intensity reaches the maximum with one sampling interval of 50 μs from the background level and decreases with 1/e-folding time of APD circuit (0.8 ms).

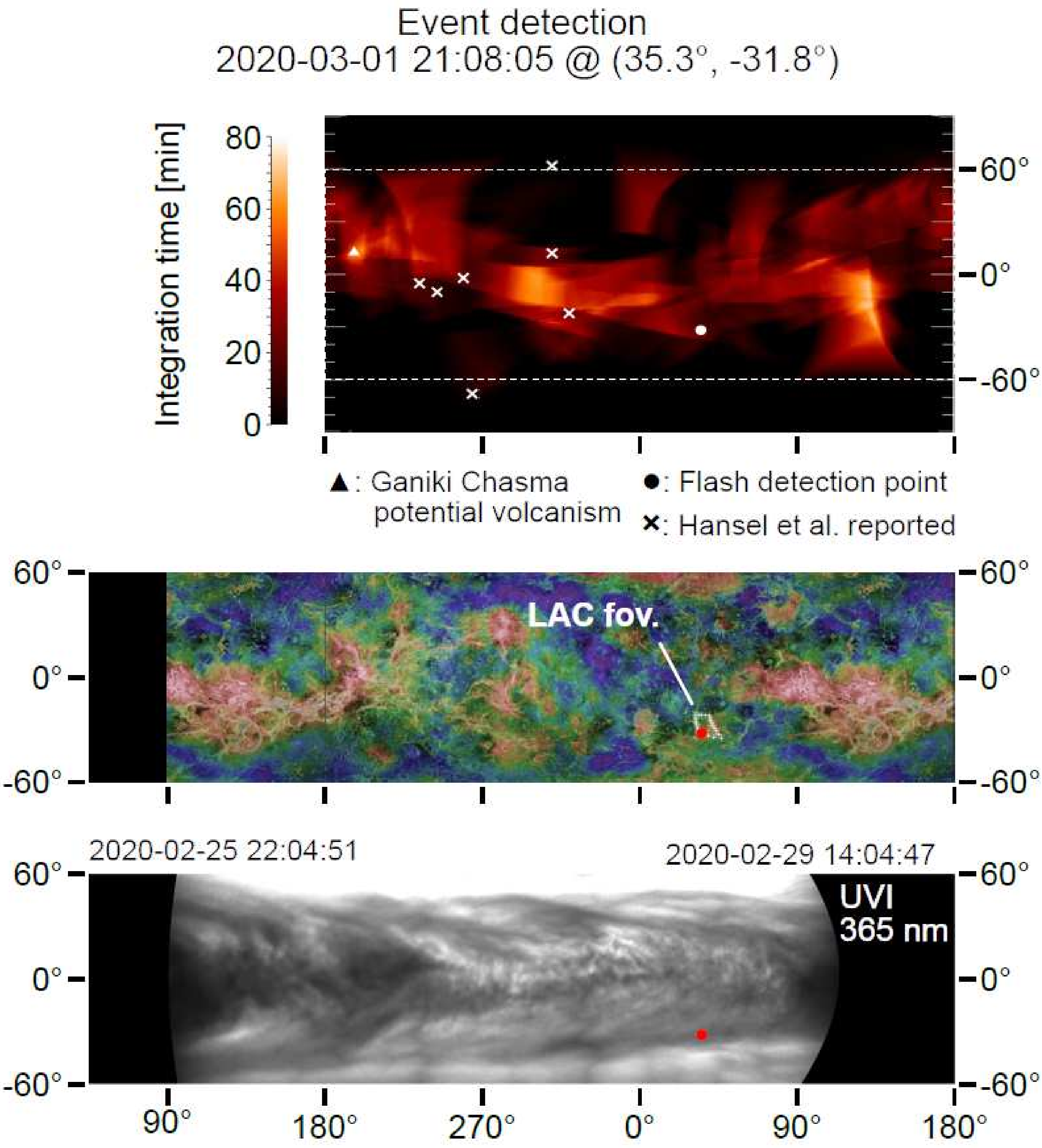

Figure 2

a (top): Map of integrated time period of observation. Color code expresses the total observation time integrated in the period from August 2016 - March 2021. The white circle denotes the location of the detected flash. White crosses and triangle show flash locations reported by Hansel et al. [1995] and the

Gniki Chasma potential volcanism, respectively. b (middle): LAC Filed of View (FOV) projected onto Venus Global Map.