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Is 2021 PH27 an active asteroid with a meteor shower detectable on Venus?

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ABSTRACT

The recently discovered near-Earth asteroid 2021 PH27 has the shortest orbital period of all known asteroids. It cannot be excluded that 2021 PH27 is also an active asteroid, as (3200) Phaethon. We intend to estimate the consequences of this hypothesis, although testing is difficult with ground-based observations during perihelion passages, due to low solar elongation. Assuming a surface activity similar to that of Phaethon, an increase in brightness of about 1.4 mag can be estimated. Since it is an asteroid with a minimum orbit intersection distance of 0.014660 ± 0.000034 au with Venus, 2021 PH27 could be the equivalent of Phaethon for the Earth and be the progenitor body of a Venusian meteor shower. A good opportunity to observe the hypothetical fireballs in Venus's atmosphere will take place on the days around 2023 June 7, when Venus will pass at the minimum distance from the nominal orbit of 2021 PH27. Another favourable date will be 2026 July 5. Finally, on 2022 March 28, the asteroid will also be at the maximum Sun elongation of about $52\overset{\circ}{.}3$ and at the aphelion of its orbit, the most favourable configuration to characterize it from the physical point of view with photometric, polarimetric, and spectroscopic observations.

Key words: minor planets, asteroids: individual: 2021 PH27.

1 INTRODUCTION

The electronic circular MPEC 2021-Q41,[1] published by the Minor Planet Center (MPC) on 2021 August 21, announced to the astronomical community the discovery of the near-Earth 2021 PH27, which holds the record for the asteroid with the shortest known orbital period: only about 114.5 d to complete a full orbit around the Sun.

This asteroid belongs to the class of Atiras, minor bodies whose orbits are completely inside the Earth's one: They have an aphelion smaller than the Earth's perihelion of 0.983 au. The Atiras – named after the first object of this class, (163693) Atira discovered in 2003 – are the smallest group of near-Earth asteroids, compared to the most populated – and easy to discover – groups: Atens (2096 bodies), Apollos (13706), and Amors (11285). Currently, 50 Atiras are known.[2] The discovery of this class of asteroids is difficult because they are observable at low angular distances from the Sun, only immediately after sunset or just before the rise of our star, when the sky is still clear and the use of a telescope becomes problematic (Ye et al. 2020).

2021 PH27 was discovered by Scott Sheppard of the Carnegie Institution of Science during the twilight of 2021 August 13 using the Dark Energy Camera connected to the Víctor M. Blanco Telescope of 4 m aperture at $F/2.94$ of the Cerro Tololo Observatory, La Serena (Chile): by exploiting 'dead time' of the instrument during twilight. Subsequent observations made by David Tholen (University of Hawaii) and Marco Micheli (ESA) confirmed the presence of this elusive member of the Solar system. 2021 PH27 has an asteroidal orbit (semimajor axis = 0.462 au, eccentricity = 0.712, inclination = $31\overset{\circ}{.}9$), with an asteroid-like Tisserand parameter with respect to Jupiter: $T_J = 11.6$.[3] From MPC astrometric data, the absolute magnitude (hereafter mag) is +17.7 with a diameter D_n value between 0.5 and 1.5 km if the geometric albedo ranges from 0.5 to 0.05: In this Letter, we assume a diameter of about 1 km. The taxonomic class, shape, and rotation period are unknown.

2 A COMPARISON BETWEEN PHAETHON AND 2021 PH27

From the MPC website, 44 astrometric observations have been made from 2021 August 13 to September 8, plus two further recovered positions of 2017 July 16, which significantly lengthened the observed time span. A total of 46 position measurements are therefore available with 0.46 arcsec rms using the NEODyS system. The minimum orbit intersection distance (MOID) with the Earth is 0.225 au – so not a particularly low value for a near-Earth – while the MOID with Venus is much lower. Taking into account the orbital uncertainties, we estimated a value of $V_{\mathrm{MOID}} = 0.014660 \pm 0.000034$ au, with the Venus-MOID flyby, which occurs when the planet has the true anomaly equal to about $82\overset{\circ}{.}68$. This low MOID value would imply, in case the asteroid was active, that it could generate a meteoroid stream swept by Venus. In other terms, 2021 PH27 could be 'the Phaethon of Venus'. In what follows, we will explore the consequences of our hypothesis, implying that the asteroid should be carefully observed during the next favourable elongation in the period 2022 March–April.

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[1] https://www.minorplanetcenter.net/mpec/K21/K21Q41.html
[2] https://minorplanetcenter.net/mpc/summary
[3] JPL Small-Body Database Browser, https://ssd.jpl.nasa.gov/

2.1 Phaethon

The active asteroid (3200) Phaethon – equivalent diameter of about 5.5 km (Taylor et al. 2019) – has a MOID with the Earth of about 0.0194 au and is considered the main source of meteoroids in the Geminid meteor shower: Together with the asteroids 2005 UD (MOID = 0.077 au) and 1999 YC (MOID = 0.247 au), they form the Phaethon–Geminid complex, which probably originated from the fragmentation of a common ancestor (Jewitt & Li 2010). The discovery of Phaethon's activity was not easy. At its maximum elongation from the Sun, Phaethon shows no sign of gas or dust emission. Only the observations made with the NASA's *STEREO-A* probe in 2009 with Phaethon near the perihelion showed photometric anomalies associated with a surface activity because the brightness increased by about 2 mag as the phase angle increased (Li & Jewitt 2013): a trend exactly opposite to what is reported about normal asteroids (Carbognani, Cellino & Caminiti 2019).

Therefore, for Phaethon, the time interval of about 24 d required to reach a Sun distance comparable to that of Venus, starting from perihelion, is sufficient to cancel any form of remotely observable activity. Indeed, deep observations made in 2017 December when Phaethon was only 0.07 au from the Earth and about 1 au from the Sun showed no signs of activity, i.e. no coma or the presence of nearby fragments larger than about 15 m in diameter (Ye et al. 2021).

Explaining the physical phenomenon that makes Phaethon active is more complex. The asteroid rotates in about 3.6 h, i.e. it is far from the classic spin-barrier value of about 2.2 h: so it is not an activity triggered by rotational disintegration as for (6478) Gault (Carbognani, Buzzoni & Stirpe 2021), also because it would not be limited to perihelion alone. The activity in conjunction with perihelion suggests the sublimation of volatile materials that cannot be cometary ices because, given the high temperatures experienced by the surface (about 1000 K near perihelion), they would have already been sublimated and – as before – it would not be limited to perihelion. According to this picture, recent near-infrared observations found no evidence of hydration on Phaethon's surface (Takir et al. 2020). The most plausible actual physical mechanism appears to be the sodium sublimation from the asteroid's rock matrix, assisted by thermal fracturing of the surface. This mechanism would explain why the Geminid meteoroids are so low in sodium (Masiero et al. 2021).

We do not know if the sodium emission encompasses the entire surface or only certain areas. What we know is that Phaethon's surface is not uniform. Radar observations made by Arecibo showed the presence of a depression more than 1 km across (probably an impact crater) near the equator and a 600 m dark region near one of the poles (Taylor et al. 2019). The photometric observations do not show a variation of the colour indices, so probably mineralogy is homogeneous, while a variation of the linear polarization between 47° and 50° of the phase angle has been observed, probably due to a change of the regolith properties (Borisov et al. 2018).

2.2 2021 PH27 activity estimate

In this section, we will assume that Phaethon and 2021 PH27 are asteroids of the same type.

Considering that the perihelion of 2021 PH27 is inferior to Phaethon's perihelion, it is reasonable to suppose that its activity could be maintained by the same physical processes, and that it shows similar properties. In particular, the activity could be restricted to a range of distances near perihelion, as in the discovery images there is not a coma. Using the observed Phaethon activity as a guide, we can make a rough estimate of the expected increase in brightness for 2021 PH27.

In the absence of constraints about the surface homogeneity of 2021 PH27, we assume for simplicity that the activity for both asteroids is evenly distributed over the surface. In this case, with the asteroids both at perihelion and considering the diameters, we can expect that the 2021 PH27 dust emission is reduced by a factor equivalent to the size ratio $(1/5.5)^2 \approx 0.03$ with respect to Phaethon. So, if the cross-section of the added dust for Phaethon in 2009 and 2012 was $C \approx 100$ km^2 (Li & Jewitt 2013), for 2021 PH27, it can be expected to be $C \approx 100 \times 0.03 \approx 3$ km^2. The geometrical cross-section of the nucleus is $C_n = \pi(D_n/2)^2 \approx 0.8$ km^2; therefore, the increasing factor of the brightness flux with respect to the bare core will be $C/C_n \approx 3.7$. Hence, an increase equal to $\Delta m = 2.5\mathrm{Log}(3.7) \approx 1.4$ mag can be expected. This brightness increase is not negligible, but the difficulty of an observation near perihelion is considerable, even for a probe like *STEREO-A*, because 2021 PH27 is an object about 3.4 mag weaker than Phaethon. If the decrease in activity with distance is the same as for Phaethon, it will not persist at large solar elongations: 2021 PH27 takes 36 d to pass from perihelion to about 0.72 au (the semimajor axis of the orbit of Venus), a value 12 d higher than Phaethon.

Still in the hypothesis that 2021 PH27 is an active asteroid similar to Phaethon, we can estimate the average density of meteoroids present along the orbit and therefore the associated meteoroid stream density. The number of meteoroids per unit of volume present in space, N_m, will be proportional to the surface of the asteroid R^2 and its orbital frequency f (the greater the number of perihelion passes, the larger the amount of ejected meteoroids). Also, it will be inversely proportional to the orbital perimeter l (the longer the orbit, the more diluted the meteoroids will be: the density variation along the orbit is not considered) and to the orbital frequency F of the intersecting planet (each Venus passage in proximity of the MOID slightly reduces the population). We can write

$$N_m \propto R^2 \left(\frac{1}{l}\right) f \left(\frac{1}{F}\right). \tag{1}$$

Using equation (1) and computing the ratio of Phaethon's number of meteoroids with 2021 PH27, we find ('P' is the index for Phaethon, 'V' for Venus, and 'E' for Earth)

$$\frac{N_P}{N_m} = \left(\frac{R_P}{R}\right)^2 \left(\frac{l}{l_P}\right) \left(\frac{f_P}{f}\right) \left(\frac{F_V}{F_E}\right) \approx 30 \times 0.3 \times 0.2 \times 1.6 \approx 3. \tag{2}$$

Therefore, assuming that the ages of streams are comparable, we can expect the mean number of meteoroids per unit volume associated with the hypothetical stream of 2021 PH27 to be about 1/3 of Geminids. From this rough estimate, the meteoroid stream hypothetically associated with 2021 PH27 appears to be not negligible.

3 OBSERVATION OF 2021 PH27

In Section 2.2, we have mentioned that, if 2021 PH27 *has a similar activity at perihelion as Phaethon*, there are good reasons to doubt that it can be detected when at the maximum elongations from the Sun, i.e. when it is observable from the Earth in the evening or morning sky in conditions similar to Venus. In any case, the times around maximum elongations are the ideal moment for its physical characterization, for photometry (determination of the rotation period, shape, and the surface colours), polarimetry, and spectroscopy (to highlight surface inhomogeneity if any).

Table 1. Summary of the maximum elongations of 2021 PH27 from the Sun in the period 2022–2026.

Data	Sun elongation (°)
28-Mar-2022	52.3
15-July-2022	44.7
11-Mar-2023	48.9
28-June-2023	49.8
22-Feb-2024	42.2
10-June-2024	50.3
4-Feb-2025	34.2
30-May-2025	37.7
16-Apr-2026	36.6
9-Aug-2026	35.1

The next favourable opportunity to observe 2021 PH27 will be on 2022 March 28 at about 10 UT when the asteroid will be at the maximum geocentric solar elongation of about 52°.3: A few hours later, at 17:40 UT, it will be in aphelion of its orbit. The asteroid will be observable in the morning sky in the months of 2022 March and April. As its declination will be negative (−13°/−22°), observers in the Southern hemisphere will be privileged. Unfortunately, the phase angle will change very little in the two months (from 91°.5 to 86°.7) or even anticipating observations to February (100°), so the characterization of the scattering properties by photometry and polarimetry will remain difficult. Other favourable conditions will then occur in future opportunities on 2022 July 15, with an evening elongation of 44°.7, and in the morning of 2023 March 11 (elongation 48°.9). For a more complete list, see Table 1.

3.1 Visibility of a hypothetical meteor shower

A further method to highlight the activity of 2021 PH27 would be to try observing meteors in Venus's atmosphere. In fact, the MOID of 2021 PH27 in respect to Venus's orbit (0.0146 au) is lower than the same MOID of Phaethon in respect to the Earth's orbit (0.0194 au), so we are in the geometric conditions to have a meteor shower in the atmosphere of Venus. The use of the atmosphere of Venus as a meteoroid detector was suggested long ago (see Ryabova, Asher & Campbell-Brown 2019 for a review) and was recently also proposed by Zhang et al. (2021) regarding comet C/2021 A1 (Leonard).

From the orbits' geometry of Venus and 2021 PH27, the MOID is only reached near the descending node of the asteroid orbit, so there is only one point of the orbit of Venus in which the observation of the meteors in the planet's atmosphere is theoretically possible. To maximize the observation probabilities, it is reasonable to observe in the periods in which Venus and 2021 PH27 are also at the minimum distance, so as to intercept the most massive part of the hypothetical meteoroid stream, but any time Venus is at the MOID with the orbit of 2021 PH27 may be the right chance.

On 2022 March 17 at about 7 UT,[4] 2021 PH27 will be at the minimum nominal distance of about 0.058 au from Venus. The planet will be clearly visible in the morning sky from the Earth, at an angular distance of about 46°.5 from the Sun, with a disc phase 0.48 and an apparent diameter of 25.7 arcsec. However, the highest probability of observing the hypothetical meteor shower is with Venus exactly at the MOID (true anomaly 82°.68), i.e. two days earlier, on 2022 March 15 at 06 UT with a Venus–Earth distance of ∼ 0.638 au, a disc phase of 0.46, and an apparent diameter of 26.4 arcsec.

[4]JPL Small-Body Database Browser, https://ssd.jpl.nasa.gov/

Table 2. Cytherocentric apparent ecliptic latitude and longitude of the Sun, Earth, and true radiant meteor shower computed for 2022 March 15 at 06 UT.

Target	Longitude (°)	Latitude (°)
Sun	034.1	−02.3
Earth	127.9	−02.6
Meteor radiant	335.8	+20.4

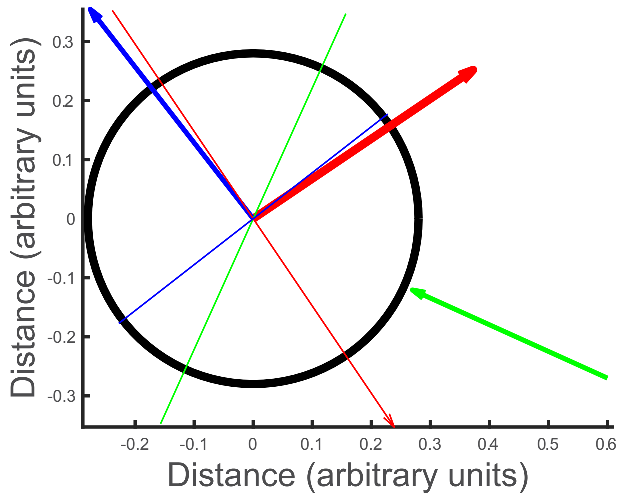

Figure 1. The projected geometry on the ecliptic plane of the Sun, radiant, and Earth as seen from Venus (black circle) on 2022 March 15, during the planet's flyby with the MOID of 2021 PH27. The planar geometry is representative of the three-dimensional geometry due to low inclinations. The *X*- and *Y*-axes are distances in arbitrary units. The red arrow indicates the direction of the Sun, the blue one that of the Earth, and the green one is the speed of the meteoroids. Thin lines with the same colour indicate the respective terminators (the terminator relative to the Sun has an arrow in Venus's motion direction). Unfortunately, the sub-radiant point is located in the diurnal hemisphere of Venus, not visible from the Earth.

The cytherocentric velocity vector of the meteoroids reaching Venus is given by the difference between the heliocentric velocity vectors of the meteoroids and Venus. It provides the direction of the true radiant as seen by a Venusian observer. The vector difference between the positions of the Sun and the Earth with Venus gives the cytherocentric directions in which the Sun and the Earth are visible, see Table 2. For practical reasons, we express all directions in terms of ecliptic coordinates.

From JPL's HORIZONS system, we retrieved the heliocentric positions and velocities of Venus and 2021 PH27 when they, respectively, reach the MOID between the two orbits, thus assuming that the orbital position and velocity of 2021 PH27 correspond to the average for the hypothetical meteoroids that it ejects. In the case of 2021 PH27, it occurs on 2022 March 10 at 8 UT (asteroid true anomaly 165°.42). The computations show that the angular distance between the Sun and the meteor radiant will be about i = 61°.5; therefore, the fraction of the Venus disc illuminated by the Sun and visible from the radiant is $k = (1 + \cos(i))/2 \approx 0.74$ and the meteors will be visible only if they fall into the remaining fraction of the disc, $k' = 1 - 0.74 = 0.26$.

On 2022 March 15, the angular distance between the Sun and the Earth seen from Venus will be about 93°.7, see Fig. 1, so it follows that the sub-radiant point – where the maximum probability

Table 3. Visibility summary of possible 2021 PH27 fireballs in Venus's atmosphere from the Earth in the period 2022–2026.

Data	SE	IF	RE	Δ	FV
15-Mar-2022	46.5	0.47	147.6	0.0631	No
25-Oct-2022	01.2	1.00	60.0	0.0165	No
7-June-2023	**45.4**	**0.48**	**40.5**	**0.3960**	**Yes**
18-Jan-2024	33.5	0.83	106.8	0.1181	No
30-Aug-2024	23.6	0.91	32.0	0.1909	No
11-Apr-2025	28.0	0.12	156.4	0.2746	No
22-Nov-2025	11.0	0.98	74.8	0.3709	No
5-July-2026	**41.7**	**0.67**	**24.6**	**0.4810**	**Yes**

The column marked 'SE' shows the Venus–Sun elongation in degrees, 'IF' the illuminated fraction of Venus's disc visible from the Earth, 'RE' the angle between the meteor radiant and the Earth in degrees, Δ the distance between Venus and 2021 PH27 in au on the date, while 'FV' shows fireball visibility in Venus's dark side of the disc. In bold type are shown the most favourable dates for observing the possible meteors in Venus's atmosphere.

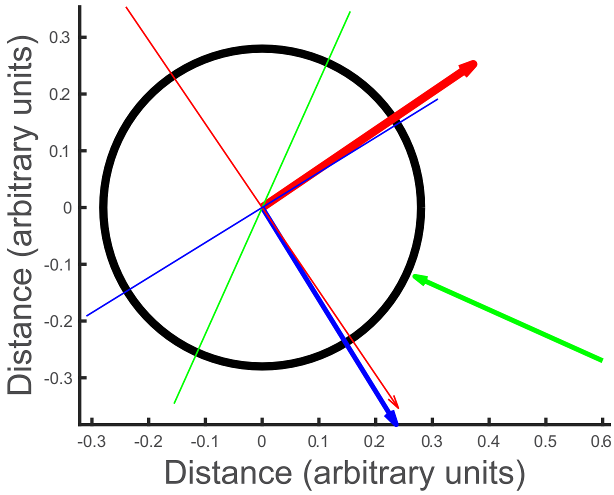

Figure 2. The geometry on the ecliptic plane of the Sun, radiant, and Earth as seen from Venus (black circle) on 2023 June 7. Fireballs may be observable because they partly fall into Venus's dark side visible from the Earth. Same colour code and axes units as in Fig. 1.

to see fireballs is – falls in the diurnal hemisphere of Venus not visible from the Earth. This encounter geometry between Venus and the hypothetical meteoroids associated with 2021 PH27 is always the same, regardless of the position of the Earth along its orbit. It follows that in the morning elongations of Venus, no impacts from 2021 PH27 meteoroids will be visible from the Earth, while the evening elongations are more favourable.

We searched for other dates when Venus is at the MOID with the orbit of 2021 PH27, and the results are listed in Table 3. Excluding the cases in which the elongation of Venus from the Sun is too low, the illuminated fraction of the planet from the Earth is too high, or when the angle between the direction of the Earth and that of the radiant is very large, there are two suitable dates for the observation of any fireballs in Venus's dark side: 2023 June 7 (see Fig. 2) and 2026 July 5 (see Fig. 3). In both cases, it is an evening elongation, with the planet comfortably observable in the early evening.

3.2 Fireball flux estimate and apparent brightness

In this final section, we make an estimate of the flux and the apparent mag that bright fireballs associated with 2021 PH27 could have.

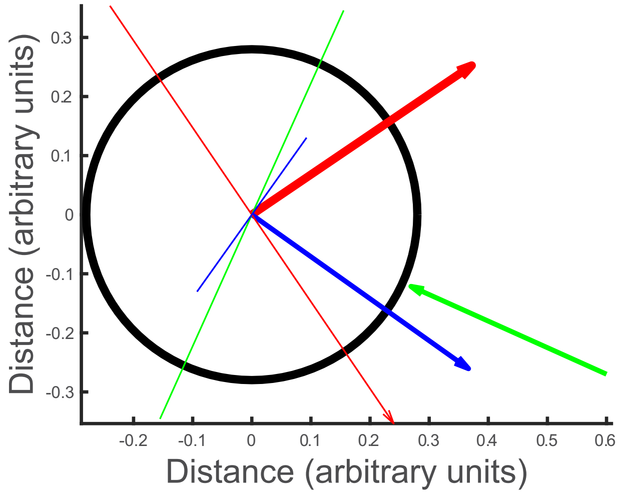

Figure 3. The geometry on the ecliptic plane of the Sun, radiant and Earth as seen from Venus (black circle) on 2026 July 5. Fireballs may be observable from the Earth because they partly fall into Venus's dark side visible from our planet. Same colour code and axes units as in Fig. 1.

The relative speed of the meteoroids with respect to the planet is about $V_{\mathrm{mr}} \approx 23.2\ \mathrm{km\,s^{-1}}$ so taking into account Venus's escape velocity $V_{\mathrm{e}} = 10.1\ \mathrm{km\,s^{-1}}$, the impact velocity in the atmosphere is $V_{\mathrm{i}} = \sqrt{V_{\mathrm{mr}}^2 + V_{\mathrm{e}}^2} \approx \sqrt{23.2^2 + 10.1^2} \approx 25.3\ \mathrm{km\,s^{-1}}$. This speed is significantly slower than Geminids (about $35\ \mathrm{km\,s^{-1}}$), thus resulting in less bright meteors for the same meteoroid mass. Considering that the zenithal hourly rate (ZHR) for Geminids is $\sim$100 $\mathrm{h^{-1}}$, that this quantity is proportional to the entry velocity and the meteoroids' number density and recalling equation (2), for the hypothetical meteoroid stream associated with 2021 PH27, we have ZHR $\approx$ 100 $\times$ (25/35) $\times$ (1/3) $\approx$ 24 $\mathrm{h^{-1}}$, an intensity comparable to our Orionids. The relation between the ZHR and the shower flux $F(< M)$, where M is the absolute mag and F is the flux measured in meteors $\mathrm{h^{-1}\ km^{-2}}$, was given by (Ehlert & Erskine 2020)

$$F\,(< +6.5) = \frac{\mathrm{ZHR}\,(13.1r - 16.5)\,(r - 1.3)^{0.748}}{37\,200\ \mathrm{km^2}}, \tag{3}$$

where r is the population index of the shower. Using the Geminids' value, $r \approx 2.6$ (Ehlert & Erskine 2020), with ZHR $\approx$ 24 $\mathrm{h^{-1}}$, we find an estimated flux $F(< +6.5) \approx 0.014$ meteors $\mathrm{h^{-1}\ km^{-2}}$.

In the evening of 2023 June 7, Venus will be at a distance of about 0.682 au from the Earth, so a meteor in the planet atmosphere will appear $\sim$30 mag fainter than a terrestrial meteor of equal brightness seen at 100 km of altitude. Under these conditions, from the Earth, we can only hope to observe the brightest fireballs, such as those of absolute mag $V \sim -12/-15$.

From the flux values of $F(< +6.5)$ above, we can get the flux of the brightest fireballs with absolute mag less than -15 by the distribution (Ehlert & Erskine 2020):

$$F\,(< M_1) = F\,(< M_2)\left[10^{(M_2 - M_1)/2.5}\right]^{1-\alpha}. \tag{4}$$

In equation (4), α is the mass index of the shower. If we assume $M_1 = -15$, $M_2 = +6.5$, and $\alpha \approx 1.95$ (same as Geminids), we get $F(< -15) \approx 10^{-9} F(< +6.5)$. Considering the impact section of Venus (a circular area projected on a plane) and the shaded fraction exposed to the radiant, $k' \approx 0.26$, one can expect to see a fireball of mag less than -15 about every 300 h. This number is clearly not very encouraging for observations, but given all the several assumptions and the absence of constraints on the real flux, it can just be considered as a rough indication maybe off by a large factor.

In the case of 2026 July 5, the geocentric distance of Venus will be about 1 au and the observation of fireballs will be even more difficult. In both cases, the diffused light from the illuminated fraction of the planet disc will be disturbed unless shielded in the optical path. Considering the uncertainties involved in the extension of the meteoroid stream, it is recommended to start observing a few days before and after the flyby of Venus with the MOID.

A much more promising alternative to ground observations is provided by space probes. The Japanese *Akatsuki* probe (JAXA)[5] is currently operating around Venus on an elliptical orbit with a period of 10 d. The distance between the spacecraft and Venus ranges from 1000 to 370 000 km. The lightning and airglow camera of *Akatsuki* can detect lightning discharge in Venusian atmosphere and would be perfect for detecting bright meteors too (Zhang et al. 2021). Unfortunately, the spacecraft operates for about 30 min each orbital revolution, a severe limitation. This makes ground observations even more important.

4 SUMMARY AND CONCLUSIONS

The purpose of this Letter is to draw observers' attention to the recently discovered Atira-type asteroid 2021 PH27. We do not know whether 2021 PH27 is an active asteroid, but based on what we know about Phaethon, this is possible. Its direct observation near perihelion (where an activity is most likely to occur) is difficult. A geocentric maximum elongation from the Sun of 2021 PH27 will be reached on 2022 March 28 at 52°.3 and will be a first good opportunity for its full physical characterization, preferably by southern observers. Other favourable conditions will then occur on 2022 July 15, with an evening elongation of 44°.7, and in the morning of 2023 March 11 (elongation 48°.9).

An anomalous brightness increase induced by the ejected dust should be detectable in the asteroid photometry. This would strongly help to better constrain the density of the hypothetical meteoroid swarm. In fact, by simply assuming an activity similar to Phaethon, it appears very difficult to observe from the ground the bright fireballs associated with any meteor shower that should impact Venus's atmosphere.

The optimum chances for the next few years will be around 2023 June 7 and 2026 July 5 during a favourable Venus-MOID flyby. In both cases, the planet will not be too far from disc dichotomy, and a part of the meteoroid stream – if any – could impact the nocturnal hemisphere partially visible from the Earth. Unfortunately, only very bright fireballs can be observed from the ground over several hours of observation, while current and future spacecrafts around the planet could have better chances from their vantage positions.

[5]https://akatsuki.isas.jaxa.jp/en/mission/

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DATA AVAILABILITY

The data underlying this Letter will be shared on reasonable request to the corresponding author.

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