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# The 2022 encounter of the outburst material from comet 73P/Schwassmann–Wachmann 3

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## ABSTRACT

The encounter of the meteoric material from 73P/Schwassmann–Wachmann 3 produced during the comet’s 1995 outburst in May 2022 provides a rare and valuable opportunity to understand a fragmenting comet. Here, we explore various ejection configurations and their impact on the meteor outburst detected in the early hours of UT 2022 May 31. We show that the dust must have been ejected  $\sim 4$  to  $5\times$  faster than calculated by water-ice sublimation model to best match the observed meteor activity. As only a small subset of particles with a narrow range of cross-section is expected to have reached the Earth, the large spread of meteor brightness likely indicates the presence of large but porous meteoroids in the trail. Other effects such as an enhanced lunar sodium tail and a visible glow from the meteoroid trail may have also occurred during the encounter.

**Key words:** comets: individual: 73P/Schwassmann–Wachmann 3 – meteorites, meteors, meteoroids.

## 1 INTRODUCTION

Most meteor showers originate from Earth’s crossing of cometary dust trails, providing means to sample cometary material without leaving Earth’s orbit. Observation of meteor showers provide a wealth of information about the recent (10–100s orbits) evolutionary history of their parents. In particular, concurrent telescopic and meteoric observation of cometary dust from their release at the parent to the manifestation as meteor shower at the Earth can provide a detailed picture of the evolution of the comet. One of the best examples is the disintegration of comet 3D/Biela and its manifestation as the Andromedid meteor shower in the 19th century (Jenniskens 2006, section 15). However, such occasion is extremely rare since most comets are only known in the era of sky surveys, and that planetary dynamics only bring a handful of dust trails to the Earth.

Jupiter-family comet (JFC) 73P/Schwassmann–Wachmann 3 is the parent comet of the  $\tau$ -Herculids, a meteor shower of which the activity is nearly absent in most years besides a strong outburst in 1930 (Nakamura 1930). 73P experienced a major outburst in 1995 September and has undergone a series of disintegration events ever since, producing more than a hundred metre-class or larger fragments in the process (e.g. Crovisier et al. 1996; Ishiguro et al. 2009; Reach et al. 2009). Independent investigations by Lüthen, Arlt & Jäger (2001), Horii, Watanabe & Sato (2008), and Rao (2021, section 4) showed that the 1995 ejecta would pass the Earth by only 0.0004 au on 2022 May 31, which may bring elevated meteor activity or even a storm. On the other hand, Wiegert et al. (2005) and alternative calculation by Rao (2021, section 3) show no close encounter with the 1995 ejecta in 2022. As pointed out by Rao (2021), the difference

lies in the assumption of ejection condition: the standard Whipple (1951) model predicts no encounter, while more powerful ejection with a speed that is a few times higher predicts a close encounter. Additional explorations by one of us (JV) shows that it only requires an ejection speed of  $2.5\times$  the Whipple model to bring millimetre-class meteoroids to the Earth.<sup>1</sup>

Increased activity of the  $\tau$ -Herculid meteor shower has been observed on 2022 May 30–31 but only reached  $\sim 1/50$  of storm level (Jenniskens 2022; Ogawa & Sugimoto 2022; Vida & Segon 2022). Since the encounter is apparently highly sensitive to ejection condition, we are interested in understanding how different configuration of dust trail can affect the visibility of the meteor outburst, as this is important for the interpretation of the meteor observation regardless of the outcome. Here, we present a suite of models constructed using available observational evidence before the meteor outburst and examine their implication on the visibility and intensity of the outburst.

## 2 MODELLING

The aforementioned researchers made a number of different, but largely compatible assumptions in their works. Lüthen et al. (2001), Horii et al. (2008), and Rao (2021) all assumed ejection at perihelion passage and tested a range of ejection speeds; Wiegert et al. (2005) simulated a suite of dust particles ejected within water-ice sublimation distance ( $\sim 3$  au) and adopted a thermophysical model to calculate ejection speeds, assuming sublimation of pure water-ice. All these approaches (or their variants) have been successfully

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<sup>1</sup><https://www.imcce.fr/recherche/campagnes-observations/meteors/2022the>, accessed 2022 May 2.

**Table 1.** Summary of predictions made by various modellers regarding the 2022 encounter of the 1995 dust trail together with the observational results. The predicted and observed geocentric speeds are in the range 11–12 km s<sup>-1</sup>.  $\beta < 0.03$ ,  $\beta < 0.006$ , and  $\beta < 0.0003$  roughly translate to dust grains larger than 10, 100  $\mu\text{m}$ , and 1 mm. ZHR is only given for the cases of  $\beta < 0.0003$  since the concept of ZHR is only applicable to optical, millimetre-class meteoroids.

Model/observation	Scenario	Peak time (UT)	Radiant ( $\alpha$ , $\delta$ )	Note
This work – model 1	Nominal speed, $\beta < 0.03$	2022 May 31 03:26	207.2°, +27.7°	Encounter with $\beta < 0.003$ dust only
–	2× speed, $\beta < 0.03$	2022 May 31 03:53	207.1°, +27.8°	Encounter with $\beta < 0.003$ dust only
–	3× speed, $\beta < 0.0003$	2022 May 31 04:30	209.5°, +28.1°	Peak ZHR=47, FWHM = 1.1 h
–	4× speed, $\beta < 0.0003$	2022 May 31 04:44	209.5°, +28.1°	Peak ZHR=76, FWHM = 2.0 h
–	5× speed, $\beta < 0.0003$	2022 May 31 04:34	209.5°, +28.1°	Peak ZHR=70, FWHM = 4.2 h
This work – model 2	2× speed, $\beta < 0.006$	-	-	No encounter
–	2.5× speed, $\beta < 0.006$	2022 May 31 05:01	209.4°, +28.3°	
Rao (2021)	-	2022 May 31 05:59	210.17°, +25.03°	
Horii et al. (2008)	-	2022 May 31 04:59	209.48°, +28.13°	
Jenniskens (2006)	-	2022 May 31 05:17	-	
Wiegert et al. (2005)	-	-	-	No encounter
Lüthen et al. (2001)	-	2022 May 31 04:55	205.40°, +29.20°	
M. Maslov <sup>a</sup>	-	2022 May 31 05:15	209.5°, +28.0°	ZHR = 600 +
M. Sato <sup>b</sup>	-	2022 May 31 05:04	-	-
CAMS <sup>c</sup>		2022 May 31 04:42	209.17°, +28.21°	FWHM = 3.5 h
GMN <sup>d</sup>		2022 May 31 04:15	208.6°, +27.7°	Peak ZHR = 22, FWHM~4 h
IPRMO <sup>e</sup>		2022 May 31 03:30–04:30	-	Peak ZHR=34, FWHM = 9 h
IMO <sup>f</sup>		2022 May 31 04:58	-	Peak ZHR=50, FWHM = 4 h

Notes. <sup>a</sup><http://feraj.ru/Radiants/Predictions/1901-2100eng/73p-ids1901-2100predeng.html>, accessed 2022 May 15.

<sup>b</sup>International Meteor Organization 2022 Meteor Shower Calendar, <https://www.imo.net/files/meteor-shower/cal2022.pdf>, accessed 2022 May 15.

<sup>c</sup>From Jenniskens (2022).

<sup>d</sup>From Vida & Segon (2022).

<sup>e</sup>From Ogawa & Sugimoto (2022).

<sup>f</sup>[https://www.imo.net/members/imo\\_live\\_shower?shower=TAH&year=2022](https://www.imo.net/members/imo_live_shower?shower=TAH&year=2022), accessed 2022 June 19.

applied on the predictions of previous meteor outbursts (see e.g. Vaubaillon et al. 2019, and the reference therein).

The case of 73P, however, is complicated due to its extensive fragmentary history. Spitzer observation of 73P’s debris trail shows that the ejection speed is likely 2× higher than predicted by classical pure-ice sublimation model (Vaubaillon & Reach 2010). Fragment C, a major component of the 73P fragment stream, was found to be highly active at the edge of the water-ice sublimation distance (Toth, Lamy & Weaver 2005). Activity or even significant outburst of JFC nuclei beyond the water-ice sublimation distance is unusual, but is far from uncommon (Kelley et al. 2013; Ye & Clark 2019).

We constructed two models with slightly different assumptions, as describe in the following text.

The first model assumes a nucleus that is active over its entire surface along the entire orbit. The purpose is to probe any meteor activity caused by distant activity of the comet. Simulated particles are released from 1995 September 12 (the approximate onset of the fragmentation Crovisier et al. 1996) to 1999 October 21 (an arbitrary date that is beyond the aphelion date of the comet, which occurred on 1998 May 27) to cover the aphelion passage of the comet. We test the classical pure-ice model (used here is the Whipple 1951, model) as well as the same model with speeds multiplied by 2×, 3×, 4×, and 5×, corresponding to approximate ejection speeds of 800, 1200, 1600, and 2000 m s<sup>-1</sup> of 1  $\mu\text{m}$  grains at 1 au. (We note that the Spitzer observation reported by Vaubaillon & Reach 2010 is consistent with the 2× model, hence these are effectively 0.5×, 1×, 1.5×, 2× the Spitzer observation.) Particles being simulated have  $\beta < 0.03$ ,<sup>2</sup> which includes meteoroids from the optical down

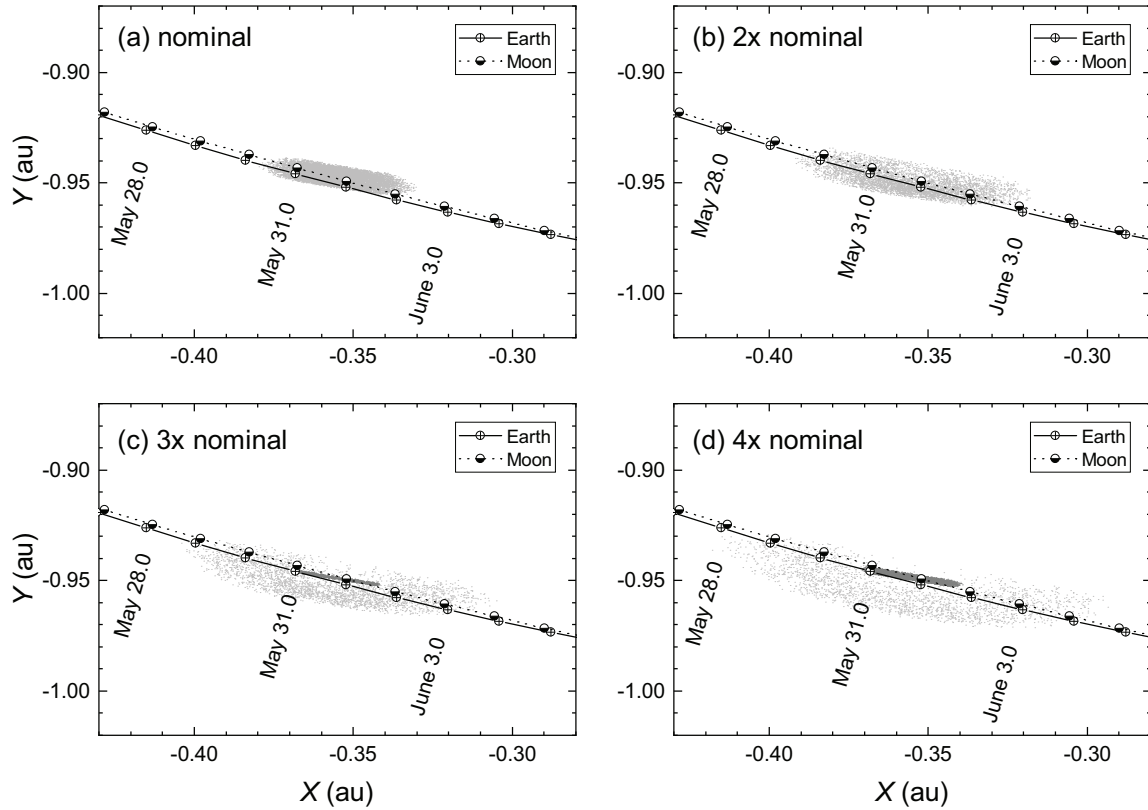
to the high-power large-aperture (HPLA) radar regime, as well as a differential size distribution of  $N(a) \propto a^{-3.7}$  following the measurement reported by Vaubaillon & Reach (2010). The amount of dust generated is inferred from the fact that the comet peaked at a visual magnitude  $V \sim 6$  during its outburst in 1995. Since the calculation by Wiegert et al. (2005) already showed that the treatment of different fragment does not significantly influence the outcome, we exclusively use the orbit solution JPL K012/14<sup>3</sup> of the main body of 73P as the parent particle in our simulation. This solution was computed using the observation from 1994 December 28 to 2000 November 4, which grossly overlap with our assumed window of activity. Particles are then integrated using a Bulirsch–Stoer integrator, with the consideration of the gravitational perturbations from the eight major planets (the Earth–Moon system is represented by a single particle at the barycentre of the two bodies), radiation pressure, as well as the Poynting–Robertson drag. We then follow the procedure described in Ye et al. (2016, section 2) to calculate the visibility and flux of meteor outbursts at the Earth.

The second model uses a more ‘conventional’ approach described by Vaubaillon, Colas & Jorda (2005a) and Vaubaillon, Colas & Jorda (2005b), which is based on a hydrodynamical ejection model (Crifo & Rodionov 1997) and assumes ejection at <3 au over the sunlit hemisphere. This model only considers meteoroids with  $\beta < 0.006$  (roughly translates to particles with a radius of 100  $\mu\text{m}$ ),

kg m<sup>-3</sup>) and radius (in m) of a spherical particle (cf. Burns, Lamy & Soter 1979).  $\beta = 0.03$  roughly translates to particles with a radius of 10  $\mu\text{m}$ . In this paper, we try to stick to  $\beta$  instead of  $a$  when discussing simulation results to eliminate the need to refer to bulk density and particle shape as both quantities are poorly constrained.

<sup>3</sup>Available from the JPL Small Body Database, [https://ssd.jpl.nasa.gov/tools/sbdb\\_lookup.html](https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html).

<sup>2</sup> $\beta$  is the ratio between radiation pressure and solar gravity and can be calculated using  $\beta = 5.74 \times 10^{-4}/(\rho_d a)$ , where  $\rho_d$ ,  $a$  are bulk density (in



**Figure 1.** Footprint of the 1995 ejecta on to Earth’s orbit on 2022 May 31 under different scenarios in model 1. Meteoroids plotted are the ones that come within 1 lunar distance from the ecliptic plane. The points in light grey represent meteoroids between  $\beta = 0.0003$  and  $0.03$  (roughly between  $10\ \mu\text{m}$  and  $1\ \text{mm}$ ), while the points in dark grey (only present in panels c and d) represent meteoroids with  $\beta < 0.0003$  (roughly  $> 1\ \text{mm}$ ). All models adopt the same dust production rate of the comet and simulate the same number of particles. The lower spatial number density seen in the  $4\times$  nominal model reflects the fact that the material is more spread out at higher ejection speed.

which are responsible for optical and typical radar meteoroids. The only ‘tweak’ to the ejection model is that we tested the  $2\times$  and  $2.5\times$  ejection speed as suggested from cursory attempts mentioned in Section 1.

Both models assume a nucleus diameter and bulk density of  $1\ \text{km}$  and  $1000\ \text{kg m}^{-3}$ .

### 3 RESULTS

Despite difference in assumptions, the two models produce similar results. These results are comparable to predictions made by other researchers, summarized in Table 1.

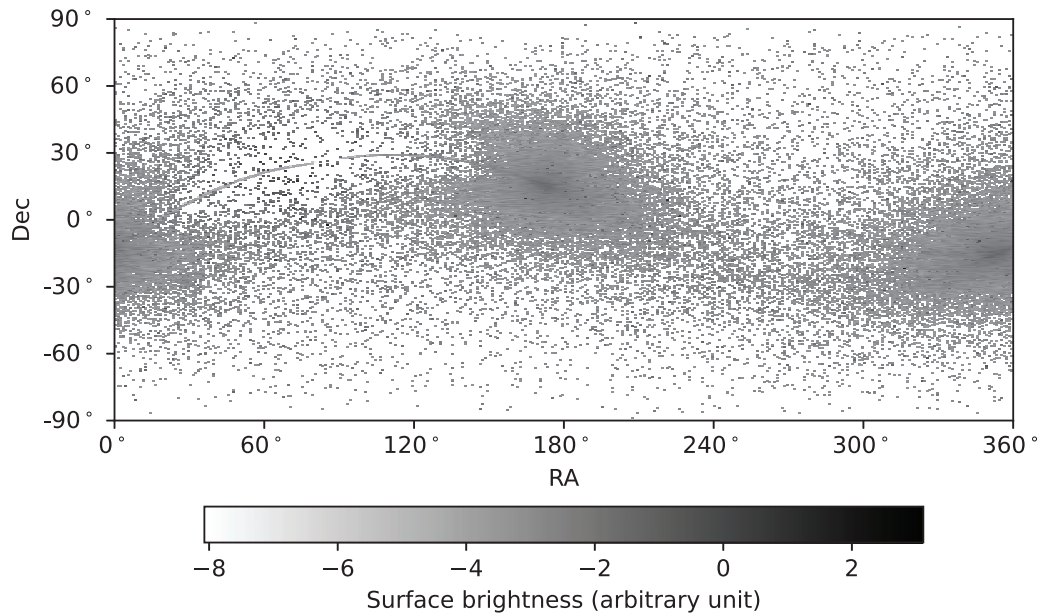
Fig. 1 shows the footprint of the simulated particles under different scenarios in model 1 on UT 2022 May 31.0. All these scenarios confirm a prolonged encounter of the debris trail. The smaller, sub-millimetre-class meteoroids tend to arrive about an hour earlier than the larger, millimetre-class ones.

We also confirm that while sub-millimetre-class meteoroids will reach the Earth in all scenarios, both models show that the millimetre-class meteoroids (responsible for meteors in optical regime) only reach the Earth when the ejection speed is at least  $2.5\times$  to  $2.75\times$  the nominal scenario. Model 1 shows that the flux of meteoroids of  $10\ \mu\text{m}$  or larger is of the order of  $10^2\ \text{km}^{-2}\ \text{h}^{-1}$  across all scenarios, dominated by meteoroids smaller than  $100\ \mu\text{m}$ . The flux of millimetre-class meteoroids, if they do reach the Earth, is around the order of  $10^{-2}\ \text{km}^{-2}\ \text{h}^{-1}$ , equivalent to a ZHR of  $\sim 50$ . (We note that the flux does not increase proportionally with an increasing

ejection speed, as material reaching the Earth is more spread out, leading to lower volume density.) We also find that the meteoroids reaching the Earth were exclusively ejected between the outburst onset (early 1995 September) to 1996 February (when the comet was at  $\sim 2.0\ \text{au}$  from the Sun in its outbound leg). This implies that meteoroids ejected from distant activity of 73P, including those from the presumed disruption of transient fragments (e.g. fragments A, D, and possibly E which split off from B some time between 1995 and 2001), will not reach the Earth in 2022.

### 4 DISCUSSION

Our simulation shows that millimetre-class meteoroids responsible for optical meteors can only reach the Earth when the ejection speed is at least 40 per cent higher than suggested by the Spitzer observation, or  $\sim 3\times$  higher than the speed calculated by Whipple (1951)’s model. This must have been the case since significant activity has been detected. The observed peak of activity, radiant, ZHR and full width at half-maximum (FWHM) of the activity profile are in general agreement with the models in Table 1. In particular, the radio observations by the International Project for Radio Meteor Observations (IPRMO), which is sensitive to smaller meteoroids, reported a peak that is slightly earlier and more prolonged than measured in optical, as expected by the models. The  $4\times$ - and  $5\times$ -Whipple-speed scenarios appear to provide the best match to the observed ZHR and FWHM (Jenniskens 2022; Vida & Segon 2022).



**Figure 2.** On-sky distribution and surface brightness (in arbitrary unit) of the 1995 trail as viewed from geocentre at UT 04 h, 2022 May 31.

A noteworthy feature of the outburst is the detection of bright meteors by many observers. Models predict that the Earth would only intercept meteoroids within a narrow range of  $0.0002 < \beta < 0.0006$ , since more massive (smaller  $\beta$ ) meteoroids would be too slow to reach the Earth. Assuming a compact spherical grain, a 0-mag  $\tau$ -Herculid meteor would need a meteoroid of a few centimetre in radius to produce (cf. Ye et al. 2016, Fig. 1). However, a typical cm-class meteoroid would require an ejection speed more than an order of magnitude higher than the speed calculated by Whipple’s model (and thus, a few times higher than the  $5\times$  model described above) to reach the Earth, which is improbable. Hence, these bright meteors likely indicate the presence of centimetre-class, porous dust aggregates that dynamically behave like compact millimetre-class meteoroids. This can also explain the observed fragility of the meteoroids from the 1995 trail but not other trails (Vida & Segon 2022; Ye et al. 2022).

We also note that the Moon is slightly closer to the centre of the trail. As a result, meteor activity (or rather, meteoroid bombardment) lasts longer on the Moon compared to the Earth. However, the dominance of  $< 100\ \mu\text{m}$  meteoroids and the low arrival speed seem to suggest that few of these events can be detected as lunar flashes from the ground. The dominance of  $< 100\ \mu\text{m}$  meteoroids, on the other hand, may provide insight into the driver of the lunar sodium tail which appears to be correlated with the rate of sporadic meteors that are of similar sizes (Baumgardner et al. 2021).

Besides manifesting into detectable meteor activities, the meteoroid trail may be close enough to the Earth so that it can be detected as a faint glow in the sky. Nakamura et al. (2000) reported a similar glow detected during the 1998 Leonid meteor storm and derived a number density of  $10^{-10}\ \text{m}^{-3}$  assuming  $10\text{-}\mu\text{m}$ -class meteoroids. Fig. 2 shows the on-sky projection of the 1995 trail at 04 h UT, 2022 May 31, as viewed from the Earth. The trail projects into two ‘lobes’ as the Earth passes through it, with one lobe centres at about  $\alpha = 170^\circ$ ,  $\delta = +20^\circ$  in the constellation of Leo, while the other lobe centres at  $\alpha = 355^\circ$ ,  $\delta = -15^\circ$  in the constellation of Equuleus. Based on the simulation results, we

estimate that the number density for the trail is of the order of  $10^{-12}$  to  $10^{-11}\ \text{m}^{-3}$ , lower than the 1998 Leonid trail but perhaps possible to detect.

## 5 CONCLUSION

We confirm that the Earth did pass very close to the debris trail produced by comet 73P/Schwassmann–Wachmann 3 during its large outburst and subsequent fragmentation in 1995 around 2022 May 31. The ejection speed of the 1995 event must have been 40 per cent higher than previously constrained by Spitzer observation, or  $\sim 3\times$  higher than value calculated by Whipple’s model, in order to explain the arrival of the swarm of millimetre-class meteoroids which have been detected near the predicted time of meteor activity. The observed activity profile of the meteor outburst is best matched by the models that assume  $4\times$  to  $5\times$  of the speed calculated by Whipple’s model.

The centre of the meteoroid trail will pass a few tenths of an au in the sunward direction of the Earth during New Moon. Given the possibly high number density of the debris trail, effects such as an enhanced lunar sodium tail may also occur. The faint glow of the trail may also be visible during the close approach.

We also note the crossing of the older 1892 and 1897 trails might have produce two separate meteor outbursts around UT 16 h of May 30 and 10 h of May 31 (Wiegert et al. 2005), as reported by Ogawa & Sugimoto (2022) and Ye et al. (2022). Given that 73P was only discovered in 1930 and has only been widely observed since the 1990s, investigations of these two meteor outbursts, along with the one produced by the 1995 trail as studied in this paper, will provide useful information and constraints about the history of the comet.

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## DATA AVAILABILITY

All data are incorporated into the article.

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