The 2022 Encounter of the Outburst Material from Comet 73P/Schwassmann–Wachmann 3

Quanzhi Ye1,2*, Jérémie Vaubaillon3
1Department of Astronomy, University of Maryland, College Park, MD 20742, USA
2Center for Space Physics, Boston University, 725 Commonwealth Ave, Boston, MA 02215, USA
3Institut de Mécanique Céleste et de Calcul des Éphémérides, IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ Paris 06, Univ. Lille, 77 Av. Denfert-Rochereau, F-75014 Paris, France.

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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 ~ 4 to 5x 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 provides 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, § 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 r-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 September 1995 and has undergone a series of disintegration events ever since, producing more than a hundred meter-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 et al. (2001), Horii et al. (2008) and Rao (2021) 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) 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 2.5x the Whipple model to bring millimeter-class meteoroids to the Earth1.

Increased activity of the r-Herculid meteor shower has been observed on 2022 May 30–31 but only reached ~ 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 MODELING

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 (~ 3 au) and adopted a thermophysical model

1 https://www.imcce.fr/recherche/campagnes-observations/meteors/2022the, accessed 2022 May 2.
to calculate ejection speeds, assuming sublimation of pure water-ice. All these approaches (or their variants) have been successfully 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 fragmentationary 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 et al. 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.

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 of 1 µm grains at 1 au. (We note that the Spitzer observation reported by Vaubaillon & Reach (2010) is consistent to calculate ejection speeds, assuming sublimation of pure water-ice beyond the water-ice sublimation distance (Toth et al. 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 also confirm that while sub-millimeter-class meteoroids will reach the Earth in all scenarios, both models show that the millimeter-class meteoroids (responsible for meteors in optical regime) only reach the Earth when the ejection speed is at least 2.5× to 2.75× the nominal scenario. Model 1 shows that the flux of meteoroids of 10 µm or larger is on the order of 10^2 km^-2 hr^-1 across all scenarios, dominated by meteoroids smaller than 100 µm. The flux of millimeter-class meteoroids, if they do reach the Earth, is around the order of 10^-2 km^-2 hr^-1, equivalent to a ZHR of ~ 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 September 1995) to February 1996 (when the comet was at ~ 2.0 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 millimeter-class meteoroids responsible for optical meteors can only reach the Earth when the ejection speed is at least 40% higher than suggested by the Spitzer observation, or ~ 3× 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-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×- and 5×-Whipple-speed scenarios appear to provide the best match to the observed ZHR and FWHM (Jenniskens 2022; Vida & Segon 2022).

An 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 < β < 0.0006, since more massive (smaller β) meteoroids would be too slow to reach the Earth. Assuming a compact spherical grain, a 0-mag τ-Herculid meteor would need a meteoroid of a few centimeter in

2 β is the ratio between radiation pressure and solar gravity and can be calculated using β = 5.74 × 10^-4/(ρ_0a) where ρ_0, a are bulk density (in kg/m³) and radius (in m) of a spherical particle (cf. Burns et al. 1979). 0.03 roughly translates to particles with a radius of 10 µm. In this paper, we try to stick to β 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.

3 Available from the JPL Small Body Database, https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html.
Table 1. Summary of predictions made by various modelers regarding the 2022 encounter of the 1995 dust trail together with the observational results. The predicted and observed geocentric speeds are between 11–12 km/s. $\beta < 0.03$, $\beta < 0.006$ and $\beta < 0.0003$ roughly translate to dust grains larger than 10, 100 $\mu$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, millimeter-class meteors.

| 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 |
| .. | 2x speed, $\beta < 0.03$ | 2022 May 31 03:53 | 207.1°, +27.8° | Encounter with $\beta < 0.003$ dust only |
| .. | 3x speed, $\beta < 0.0003$ | 2022 May 31 04:30 | 209.5°, +28.1° | Peak ZHR=47, FWHM=1.1 hr |
| .. | 4x speed, $\beta < 0.0003$ | 2022 May 31 04:44 | 209.5°, +28.1° | Peak ZHR=76, FWHM=2.0 hr |
| .. | 5x speed, $\beta < 0.0003$ | 2022 May 31 04:34 | 209.5°, +28.1° | Peak ZHR=70, FWHM=4.2 hr |
| This work – model 2 | 2x speed, $\beta < 0.006$ | 2022 May 31 05:01 | 209.4°, +28.3° | No encounter |
| .. | 2.5x speed, $\beta < 0.006$ | 2022 May 31 05:01 | 209.4°, +28.3° | No encounter |
| 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 | - | - |
| Wiepert et al. (2005) | - | - | - | - |
| Lüthen et al. (2001) | - | 2022 May 31 04:55 | 205.4°, +29.20° | - |
| M. Maslov$^a$ | - | 2022 May 31 05:15 | 209.5°, +28.0° | ZHR=600+ |
| M. Sato$^b$ | - | 2022 May 31 05:04 | - | - |
| CAMS$^c$ | 2022 May 31 04:24 | 209.17°, +28.21° | FWHM=3.5 hr |
| GMN$^d$ | 2022 May 31 04:15 | 208.6°, +27.7° | Peak ZHR=22, FWHM~4 hr |
| IPRM$^e$ | 2022 May 31 03:30-04:30 | - | Peak ZHR=34, FWHM>9 hr |
| IMO$^f$ | 2022 May 31 04:58 | - | Peak ZHR=50, FWHM=4 hr |

$^a$ http://feraj.ru/Radiants/Predictions/1991-2100eng/73p-ids1901-2100predeng.html, accessed 2022 May 15.

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

$^c$ From Jenniskens (2022).

$^d$ From Vida & Segon (2022).

$^e$ From Ogawa & Sugimoto (2022).

$^f$ https://www.imo.net/members/imo_live_shower?shower=TAH&year=2022, accessed 2022 June 19.

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 5x model described above) to reach the Earth, which is improbable. Hence, these bright meteors likely indicate the presence of centimeter-class, porous dust aggregates that dynamically behave like compact millimeter-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 center 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 $<100\mu$m meteoroids as well as the low arrival speed seem to suggest that few of these events can be detected as lunar flashes from the ground. The dominance of $<100\mu$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 $10^{-10}$ m$^{-3}$ assuming 10-$\mu$m-class meteoroids. Figure 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 centers at about $\alpha = 170^\circ$, $\delta = +20^\circ$ in the constellation of Leo, while the other lobe centers 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 in the order of $10^{-12}$ to $10^{-11}$ 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% higher than previously constrained by Spitzer observation, or~3x higher than value calculated by Whipple’s model, in order to explain the arrival of the swarm of millimeter-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 4x to 5x of the speed calculated by Whipple’s model.

The center 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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Figure 1. Footprint of the 1995 ejecta onto 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 $10\,\mu$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.

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

All data are incorporated into the article.

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