Ongoing meteor work

Will Comet 73P/Schwassman-Wachmann 3 produce a meteor outburst in 2022?

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Comet 73P/Schwassmann-Wachmann 3, a member of the Jupiter family of comets, broke into several fragments in the autumn of 1995. A dramatic increase in the comet's intrinsic brightness was then seen, suggestive of a massive expulsion of dust. Orbiting the Sun about every 5.4 years, the comet has continued to disintegrate since its initial disruption. Dozens of fragments have since been identified in subsequent near-Earth passages. Three independent studies have investigated the prospects of Earth's passage through its trail of freshly ejected material which could lead to a meteor shower. One study showed that Earth will fail to interact with the ejected material, while the other two suggest a direct interaction with the trail, thus possibly producing an outburst of meteor activity at the end of May 2022.
Using an N-body integrator, we found that all three studies are plausible. However, the occurrence of a meteor shower/outburst requires a rather unique set of circumstances: One that assumes a larger-than-normal preponderance of the particles are subsequently ejected at sufficiently high velocities to overcome the effects of solar radiation pressure. Such material would tend to migrate forward of the comet's direction of motion around the Sun, ultimately colliding with Earth. We find that any detectable meteor activity would reach a maximum on 2022 May 31.21 UTC, with a mean radiant position of $\alpha = 208.^\circ 35$, $\delta = 27.^\circ 45$ (J2000.0).

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1 Introduction

Meteor observing is usually a slow and meditative pursuit, but occasionally it can turn dramatic. Most meteor showers are fairly predictable. Occasionally a bright fireball will blaze into view, but there is always a chance of witnessing something truly new and unexpected – perhaps even when no shower was predicted at all.

And at the end of May 2022 things could turn exciting.

In the fall of 1995, comet 73P/Schwassmann-Wachmann 3 fractured into several pieces and left a trail of fragments in its wake which the Earth might encounter during the overnight hours of 2022 May 30–31.

On that night, a meteor shower might erupt ranking with the January Quadrantids or December Geminids; annual displays which are normally the richest of the year. Yet, there is also a small chance of something extraordinary – perhaps one of the most dramatic meteor displays since the spectacular Leonid showers which occurred around the turn of this century, with a large fraction of the meteors being bright.

Or perhaps, visually, nothing at all will be seen.

The possibility of Earth interacting with the dross of a fragmented comet may sound familiar. Indeed, most astronomy texts often make reference to the famous case regarding the splitting of comet 3D/Biela in 1842 or early 1843 and its contemporaneous association with spectacular meteor storms occurring in 1872 and again in 1885.

The question is, might there be hope for a similar performance resulting from the recent break-up of comet 73P/Schwassmann-Wachmann 3?

2 Comet 73P/Schwassmann-Wachmann 3

Diminutive visitor

Comet 73P/Schwassmann-Wachmann 3 (hereon designated "SW 3") was the third comet found by German astronomers Friedrich Carl Arnold Schwassmann and Arno Arthur Wachmann in the early 20th century. After its discovery on photographic plates exposed on 1930 May 2 at Hamburg Observatory (Bergedorf) for the regular minor planet survey, orbit calculations quickly revealed that the comet would pass only 0.0616 au from the Earth on 1930 May 31.

Astronomers believe that SW 3's nucleus probably measures only around 1.3 km in diameter (Boehnhardt et al., 2002) – hardly a significant celestial body. Consequently, the comet is intrinsically quite faint. For this reason, its peak brightness in 1930 was estimated to be between magnitudes +6 and +7. SW 3 was also seen to possess a rather faint tail measuring about $\frac{1}{2}^\circ$ in length (Kronk, 1984).

Even though SW 3 orbits the Sun about every 5.4 years, 1930 was the last time anyone saw it for quite a while. In fact, between 1935 and 1974, SW 3 came and went eight times without being observed. It finally was caught on photographs taken in Australia in 1979 (magnitude +12.5 on March 19 when 1.4359 au from Earth), missed in 1985, and recovered again in 1990 (magnitude +9.0 on April 17 when 0.3661 au from Earth; its best apparition since 1930).

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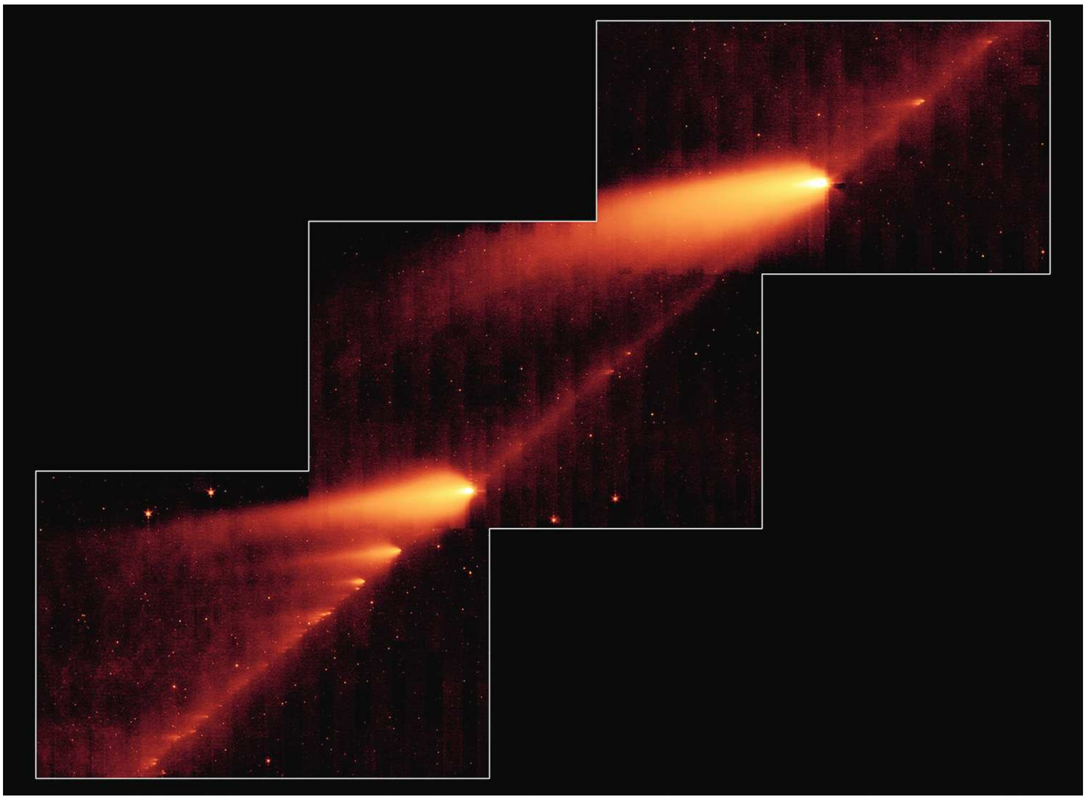

Figure 1 – Recorded on 2006 May 4–6 by the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope, this image captures about 45 of 58 alphabetically cataloged large comet fragments. The brightest fragment at the upper right of the track is Fragment C. Bright fragment B is below and left of center. Spitzer's infrared view also captures the trail of dust left over as the comet deteriorated during previous perihelion passages in 1995 and 2001. Emission from the dust particles warmed by sunlight appears to fill the space along the cometary orbit. Image credit: NASA, JPL, Caltech.

Surprise!

Astronomers expected SW 3 to make another uneventful return in the fall of 1995. From September 8 through 13, however, radio-wavelength observations of the comet's emissions made at the Observatoire de Paris-Meudon's Nancay Radio Telescope, indicated a significant increase in Hydroxide (OH^-), with peak production at $2.22 \pm 0.22 \times 10^{29}$ molecules per second (Crovisier et al., 1996). This is only a factor of 10 below the peak production rates observed for the much larger Halley's Comet during its 1986 apparition (Wiegert et al., 2005).

Then, during mid-October, 1995, the Central Bureau for Astronomical Telegrams suddenly began receiving "numerous reports from observers worldwide of independent discoveries" (Green, 1995a) of a comet verging on naked-eye visibility that had been sighted low in the western sky during evening twilight and sporting a dust tail 1° long.

This, however, wasn't a "new" comet at all – it was 73P/Schwassmann-Wachmann 3!

This was a huge surprise, because that year the comet never came closer to Earth than 1.3114 au on October 17. Predictively, it should have appeared no brighter than about magnitude +12; a challenging target even through large amateur telescopes. And yet there it was, shining $6\frac{1}{2}$ magnitudes brighter than anticipated – a nearly *400-fold increase* in luminous intensity! Here was a classic demonstration of how a comet can go around the Sun on numerous occasions as a staid member of the solar community, and then abruptly and unpredictably undergo some sort of violent change.

As to the cause of this tremendous outburst, the answer came on 1995 December 12–13, when observations of SW 3 made at the European Southern Observatory in La Silla, Chile revealed "at least four separate brightness peaks in the coma" (Green, 1995b). SW 3's tiny nucleus had fragmented, but unlike 3D/Biela, which simply broke in two, SW 3 apparently fractured into *four parts*.

On IAUC No. 6301, dated 1996 February 1 (Marsden, 1996), comet investigator, Zdeněk Sekanina determined that component B broke off from the primary component C "most probably about 1995 Oct. 24" ... evidently followed by a secondary splitting of component B, which gave birth to component A on, or about Dec. 1. As for component D, it seems it might have separated from C in late November. Noted Brian G. Marsden, then-Director of the Central Bureau for Astronomical Telegrams: "There now appears to be no escape from the conclusion that the brightness outburst, which apparently occurred between Sept. 5 and 8, preceded the first breakup episode by at least six weeks."

The comet was still quite bright on its next visit in the fall of 2000, when many people saw it even though it was poorly placed for observation. Two of the fragments spotted in 1995 (known as B and C) had returned, together with a new one (E), which probably was released (but undetected) during the 1995 return. C was presumed to be the largest remnant of the original comet and was thus designated as the main object, with B (about one-third the size of C) and E appearing as individual small comets trailing more than $\frac{1}{2}^{\circ}$ behind C.

In the spring of 2006, the disintegrating comet made its next return appearance. Initially, astronomers counted at least eight remnants: big fragments B and C plus smaller fragments G, H, J, L, M and N. During this apparition some of the fragments were themselves forming their own sub-fragments.

On 2006 April 18, the Hubble Space Telescope recorded dozens of pieces of fragments shed primarily by B and G (Hubblesite, 2006). Between May 4 and 6, it was the Spitzer Space Telescope's turn to image the comet (Figure 1); using its Infrared Array Camera (IRAC) it was able to observe 45 of 58 known fragments (NASA, 2006). The main fragment, C, passed closest to Earth on May 13 at a distance of 0.0735 au, with fragments B and E passing even closer at 0.0515 and 0.0505 au respectively. In all, SW 3 broke into more than 68 fragments. Perihelion was on June 9, with the comet passing the Sun at a distance of 0.9391 au.

The comet would not return to the vicinity of the Sun until 2011 October; another unfavorable apparition.

SW 3's most recent perihelion was in 2017 March. Big fragment C was still chiefly intact, but was then seen accompanied by a smaller fragment designated as BT. So, it appears that the comet was then continuing to slowly break apart, shedding new pieces with each return through the inner solar system.

Its next perihelion will occur on 2022 August 25 at a distance of 0.9729 au.

3 Meteors from 73P?

Shortly after SW 3 was discovered in 1930, two astronomers at Kwasan Observatory (Kyoto, Japan) calculated an orbit and from this, one (Shibata) predicted a possible meteor shower when the Earth passed close to the comet's node on June 9 (Nakamura, 1930). The assumed radiant was located in northern Hercules, near the fourth magnitude star Tau (τ) Herculis. The potential new meteor shower was thus christened the "Tau Herculids" (later designated #61 TAH at the IAU Meteor Data Center).

Meteoroids presumably shed by SW 3 had been sighted as meteors chiefly by Japanese observers during the final week of May into early June 1930. The observed activity, however, was very weak, producing only several possible shower members. On June 8, an announcement regarding the potential of a strong meteor shower associated with SW 3 was widely circulated in newspapers around the globe (Kronk, 1988).

Indeed, on June 9, from Kwasan Observatory in Kyoto, Japan, an outburst of 59 meteors in one hour (9:51 to 10:51 p.m. local time) was reported. On the following night, again from the same location, 36 meteors were sighted in only 30 minutes (an event rate of 72 meteors per hour) (Jenniskens, 1995).

But there is a problem in accepting that these events actually took place. The only person who claimed to see these outbursts was Kaname Nakamura, who commented that "... all of these meteors were very faint and only a few of them were as bright as 4th magnitude." However, there was a full Moon on June 11, so his observations on June 9 must have been conducted under the bright-sky conditions of a waxing gibbous Moon. Moreover, Nakamura noted that on both nights (June 9 and 10), "... bright lunar haloes were high above the southern horizon." So, despite a nearly full Moon illuminating a moonlight-scattering layer of high-altitude cirrus or cirrostratus clouds, Nakamura still managed to somehow see a bevy of very faint meteors on consecutive nights. Even the director of the Kwasan Observatory, Issei Yamamoto, later noted that "Mr. Nakamura was practically the only observer" among staff members of the observatory.[a]

Elsewhere however, Nakamura-san's suggested meteor activity was conspicuously absent. Members of the meteor section of the British Astronomical Society failed to see a single member of the Tau Herculid stream on the nights of June 5, 7 and 9, putting the blame squarely on the bright moonlight.

Any reports of possible Tau Herculid activity in the years following 1930 have ranged from exceedingly sparse to non-existent. Some meteoroid orbits inferred from meteor streaks on photographic plates taken from 1963 and 1971 (Southworth & Hawkins, 1963, pages 274 & 280; Lindblad, 1971, pages 19 & 23) have been identified with this stream.

Finally, during this past decade, minor activity from the Tau Herculids was definitely confirmed: On 2011 June 2, NASA Cameras for all-sky meteor surveillance in California (CAMS), photographed 3 members of this stream between 4^{h} and 12.2^{h} UTC.[b] Additionally, on 2017 May 30–31, between 23:39 and 00:45 UTC, five shower members were again captured by CAMS. Lüthen et al. (2001) had forecast possible activity for both years from a dust trail shed by SW 3 in 1941 and another in 1952. Actually, both predictions were thought to be somewhat dubious since the respective miss distances were considered fairly large (0.0011 au and 0.0013 au, respectively).

[a]Nakamura-san's credibility is further strained regarding another meteor shower, one in 1921, the June Boötids ("Pons-Winneckids"). During the interval from June 26th to July 9th, and observing under skies that varied from clear to mostly cloudy, Nakamura reported notable meteor outbursts on July 3rd (153-meteors in only 35 minutes; an hourly rate of 262) and July 5th (91-meteors in 41 minutes; an hourly rate of 133). Nakamura claimed to have "very sensitive eyes," as his daily estimates of the mean magnitudes of these meteors varied from 4.5 to 5.0. William F. Denning, a highly regarded British meteor observer in his own right, voiced some incredulity about Nakamura's observations, "unless," he wrote (Denning, 1922), "Nakamura is able to discern meteors of 6th, 7th and 8th magnitudes."

[b]On 2011, June 1, Pierre Martin, observing from Bootland Farm, Ontario, Canada reported that he, "... signed on at 11:20 p.m. EDT. I was able to stay on for 37 minutes before the next wave of clouds arrived. During this time, I saw a few sporadics and a single gorgeous Tau Herculid! It was a mag −1 golden-yellow meteor that descended below Lyra in the east, ending near the double star Albireo. It had a thick wake! Checking the plot on this one confirms a perfect alignment with the TAH radiant." Taken from the now-defunct Meteorobs Internet mailing list.

Ingredients for a meteor shower

The birth, life and death of a meteor stream is reasonably well understood, at least in broad outline. Whenever a comet comes near the warmth of the Sun a little of its frozen nucleus sublimates, shedding clouds of dust and rubble. In time, this material spreads out along the comet's orbit, then gradually diffuses away from the orbit. An intense shower occurs when Earth passes – albeit briefly – through a thin, concentrated band of debris inside the much larger dust stream. These dense filaments are typically found relatively near the parent comet, and in most cases, they were probably shed from it only in recent centuries.

All the ejected particles, regardless of size and unless perturbed, stay closely confined to the plane of the comet's orbit – at least until, in time, the stream degrades and drifts apart. Gravitational perturbations by the planets are a major factor in shifting and eventually breaking up a meteor stream. Tracking all of these influences is what meteor shower forecasting is about.

The old meteoroids that have had time to become widely scattered are the ones that produce the ordinary, weak annual shower. The narrow, densest part of the swarm is a ribbon whose width is poorly known; in fact, the "ribbon" may actually be a more complicated structure consisting of thin bands and sheaves.

Testing for 73P/Schwassmann-Wachmann 3

In 2004, astronomer Jérémie Vaubaillon, at the Institute for Celestial Mechanics and Computation of Ephemerides (IMCCE) in Paris, France, introduced a new type of model for the formation and evolution of comet dust trails. His ejection model is primarily based on a hydrodynamic model by Crifo & Rodionov (1997) and takes into account comets at heliocentric distances of less than 3 au which ultimately produce clouds of dusty debris. The meteoroids are ejected in a uniform manner from the comet's spherically symmetric sunlit hemisphere. For comet SW 3, numerical simulations were performed (Wiegert et al., 2005) using nearly two million particle ejections from 1801 to 2006, assigned to five size bins ranging from 0.1 to 100 mm. The typical ejection (escape) velocity V is computed in the sunlit hemisphere (Vaubaillon et al., 2005a,b), as a function of comet nucleus properties (size, fraction of active area etc.), particle size, ejection sub-solar angle and heliocentric distance, using a Monte-Carlo method and leading to a range in V up to 20 m/s (±20 m/s), with V falling to 0 m/s at sub-solar angle = 90°.

As has been previously noted, save for a scattered few, no meteor activity of consequence associated with comet SW 3 has been reported since 1930. (Even here, there is some contention as to whether heightened activity noted in that year actually took place.)

However, the nucleus fragmented in 1995 and has continued to disintegrate, producing a fresh trail of cometary material. This combined with the Earth's orbit positioned very close to the descending node of the comet, has raised the prospects for a possible meteor outburst or perhaps even a storm similar to what happened with 3D/Biela; a possibility that should certainly be investigated.

Wiegert et al. (2005) discussed the exceptionally close (0.05 to 0.07 au) approach in May 2006 of comet SW 3 and its associated fragments relative to Earth. In that paper the authors noted that, "... a swarm of comet fragments of various sizes, ranging from kilometer sized on down, will pass near the Earth in 2006, and the possibility exists that the τ Herculid shower, typically unimpressive, could be dramatically stronger than usual."

Ultimately however, such a possibility for enhanced activity was ruled out (as will later to be shown to be correct): "... partly (as a result) of the dynamics of the parent comet, which suffers frequent close encounters with Jupiter," (Figure 2) "and partly of the location and timing of the splitting event, which produces a distribution of meteoroids that does not approach the Earth particularly closely." (Wiegert et al., ibid.)

After 2006, the next possible Earth encounter for meteor activity is in 2022, but it would not originate from meteoroids released during the 1995 splitting of SW 3's nucleus. Rather, meteoroids released during pre-discovery apparitions in 1892 and 1897 reached the Earth at the end of May that year. A maximum ZHR (zenithal hourly rate) from these 19th century meteoroids of 10 is back-predicted, but based on Vaubaillon's model, no interaction of Earth with cometary material released during 1995 is forecast for 2022 (Figure 3).

Let's dance!

Out of curiosity, we attempted to model the meteoroid stream associated with the 1995 break-up of comet SW 3 using a different methodology. For the task of providing adequate orbital simulations for particles relating

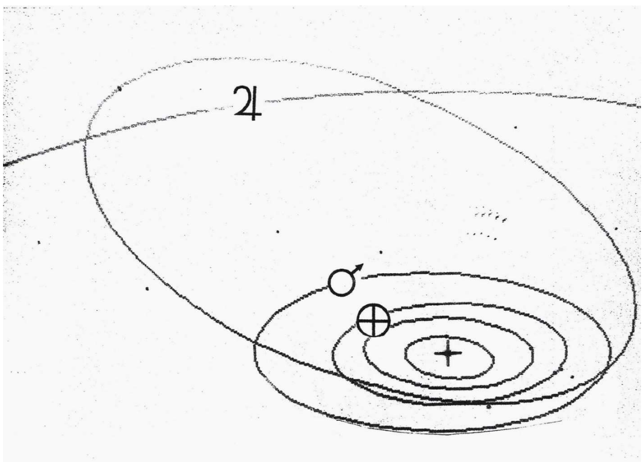

Figure 2 – Orbit of comet 73P/Schwassmann-Wachmann 3 (SW 3). It is a member of Jupiter's "comet family," a group of about 400 short period comets with aphelia near the orbit of Jupiter. The comet's orbital period is roughly 5.4 years and it arrived at aphelion in 2019 late December... 5.213 au from the Sun. Its close proximity to Jupiter's orbit means that occasionally it will be perturbed by that big planet's gravitational field. Since the comet's discovery in 1930, it has approached to within 0.68 au of Jupiter in 1953 October and within 0.29 au in 1965 November. It will make a similarly close approach to Jupiter (0.29 au) in 2025 February.

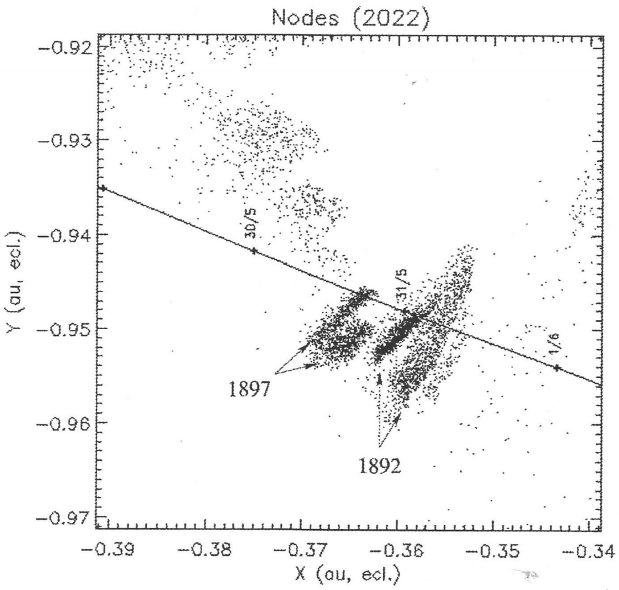

Figure 3 – The nodal crossing points of meteoroids (depicted as small dots) ejected from SW 3 at all perihelion passages back to 1801 based on the Vaubaillon model, plotted relative to the Earth's orbit for the year 2022. Only meteoroids whose descending node occurred within one week either before or after Earth's passage are shown. The relevant dust trails are marked by arrows indicating their year of origin. Earth interacts with dust ejected from 1892 and 1897, but not with the dust trail produced by the fracture of SW 3's nucleus in 1995. Image credit: Jérémie Vaubaillon (original source Wiegert 2005, figure 6).

to SW 3, the computer program Dance of the Planets (Arc Science, 1994) was chosen. It is an N-body integrator; the incremental movement of each body due to the gravitational influence of all others is continuously calculated, closely approximating the action of gravitation. One unfortunate limitation of the program is it does not take into account non-gravitational forces; an effect that accelerates or decelerates a comet's motion, changing its orbital period.

Our attempt was made solely to corroborate Vaubaillon's model prediction as to how closely SW 3 meteoroids would approach Earth. First, epoch 1995 positions of 73P/Schwassmann-Wachmann 3 were obtained from orbital elements developed by Kenji Muraoka, derived from 226 observations (1989 to 1996) (Yoshida, 1997). Second, to simulate a trail of meteoroids, an additional 19 comets (the maximum possible for this software program) were generated, positioned along a radius vector diametrically opposed to the Sun. Third, for the representation of the respective meteoroid "cloud" orbits, Muraoka's orbital elements from the 1995 apparition of SW 3 were copied onto the program's "CMT" files:

$$\begin{aligned} T &= \text{1995 September 22.88978 UTC} \\ q &= 0.93278 \\ e &= 0.694848 \\ \omega &= 198\overset{\circ}{.}7693 \\ \Omega &= 69\overset{\circ}{.}9466 \\ i &= 11\overset{\circ}{.}4239 \end{aligned}$$

The only alterations made were in the respective perihelion distances (q) of the other 19 comets from the Sun. Starting with "parent comet" 73P/Schwassmann-Wachmann 3 at 0.93278 au, all 20 comets were aligned within a space measuring 0.01076 au (1.609 million km or 1 million miles); each comet separated incrementally by increasing distances from the Sun of 0.00053789 au (80 000 km or 50 000 miles).

The speed of the orbital simulation is set using the tunable Dance parameter "Pace" (the apparent time acceleration). Very large values can diminish simulation accuracy. "True" is real time. For heliocentric space views, the maximum pace simulated by Dance is 240k; one-minute equates to about 385 years. It was determined for adequately simulating a trail of meteoroids, the Pace should be set at a much slower unit of 1000 (where one minute equates to roughly 16 years). There is also a tunable magnification function, "Zoom" which for heliocentric space views runs upwards to 512×. A Zoom of 1× corresponds to a naked-eye view. For our simulations a Zoom of 64× was employed.

So, starting from perihelion in 1995, the 20 comets were set into motion at Pace = 1000 and Zoom = 64×. Moving forward in time, the comets gradually separated from each other along their corresponding orbital paths.

Moving forward in time from 1995 to 2006, the "parent" comet, SW 3, and the next six comets in the presumed meteoroid trail, swept past the Earth near the comet's descending node at distances of less than 0.2 au as shown in Table 1.

Table 1 – SW 3's 1995 meteoroid trail proximity to Sun and Earth; r = heliocentric distance, Δ = geocentric distance when comet reaches descending node.

Comet	UTC Date	r (au)	Δ (au)
SW 3	2006 May 20.27	0.960	0.184
#2	2006 May 23.60	0.961	0.132
#3	2006 May 26.95	0.961	0.084
#4	2006 May 30.29	0.962	0.053
#5	2006 Jun. 2.69	0.962	0.069
#6	2006 Jun. 5.96	0.963	0.113
#7	2006 Jun. 9.39	0.963	0.164

In this simulation, the parent comet arrived at perigee *one week after* the actual perigee passage of the main fragment ("C") and two smaller ones ("B" and "E"). This likely can be attributed to nongravitational forces on the fragments as they approached the Sun. Such a relatively large displacement implies that the comet is either very active or very low-mass (in this case, more likely the latter as opposed to the former).

However, these values support the 2005 findings of Wiegert and his colleagues, i.e., in spite of this very close approach of the comet and its fragments to Earth, even a distance of ~0.05 au was not close enough to produce any noticeable meteor activity.

As for 2022, once again Earth will apparently be spared from any interaction with material shed by the 1995 break-up of SW 3. Using Dance, it was determined that Earth will arrive at the descending node of SW 3, 65.9 days *prior* to the arrival of the comet and its accompanying train of meteoroids (Figure 4). So, it would seem that, as was the case in 2006, there is no possibility of an outburst or enhancement of the Tau Herculid shower, again corroborating the findings of Wiegert et al. using the Vaubaillon model.

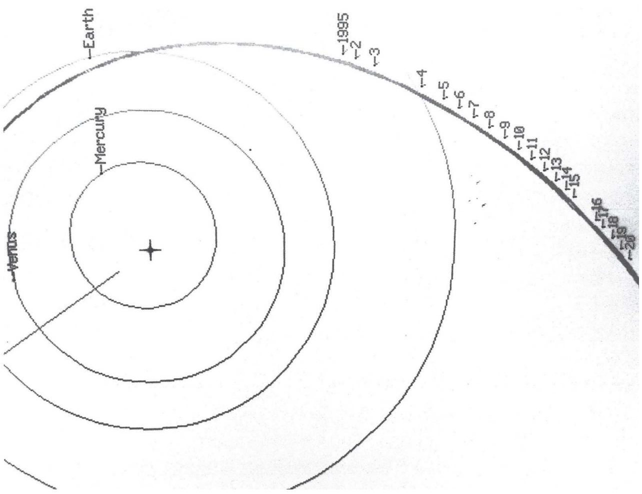

Figure 4 – Positions of Earth, SW 3 and presumed train of meteoroids on 2022 May 31 using Dance of the Planets orbital simulator. Note that the orbits of the comet ("1995") and its meteoroid train appear somewhat displaced from their original 1995 orbits – the year of the breakup of the comet nucleus. Assuming meteoroids are *trailing behind* the parent comet, no interaction with the Earth can take place, supporting the findings of the Vaubaillon model.

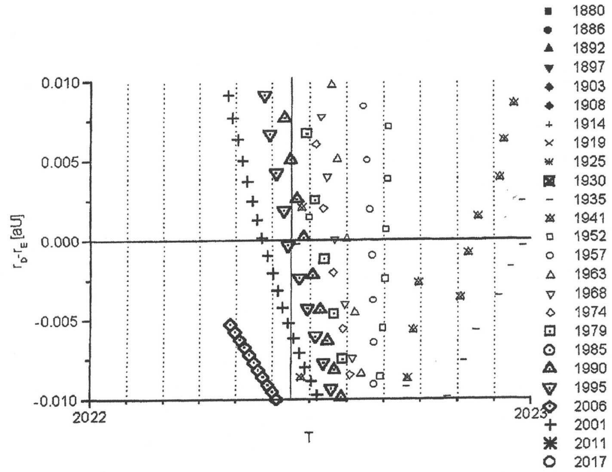

Figure 5 – Diagram from the study by Lüthen et al. (2001), depicting the distance of the particle at the node from the orbit of Earth ($r_\mathrm{D} - r_\mathrm{E}$) as a function of perihelion time T. The particles reaching the node at the same time as Earth are marked with the vertical line. Dust trails of particles from parent comet SW 3 that reach perihelion in 2022 are shown. On May 31.21 UTC, Earth will pass the richly populated 1995 dust trail at a distance of only about 0.0004 au. Image credit: Rainer Arlt.

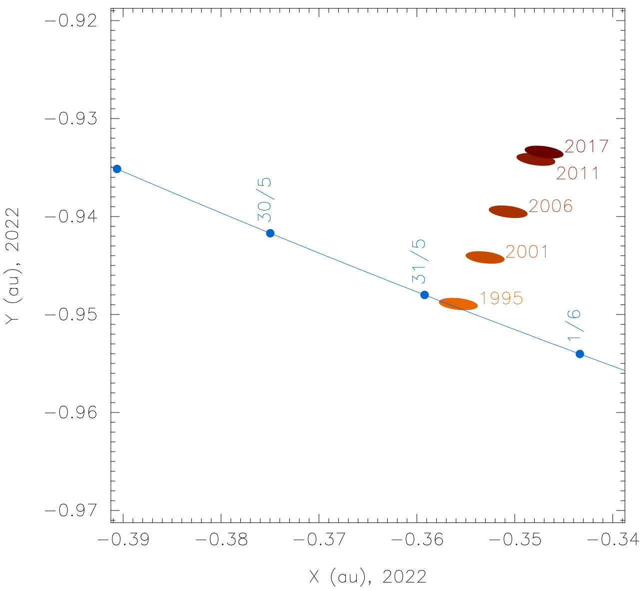

Figure 6 – Diagram, on the same scale as Figure 3, depicting the location of the intersection with the ecliptic plane of the dust trails of 1995, 2001, 2006, 2011 and 2017, as computed in table 1 of the study by Horii et al. (2008). The continuous line represents the path of the Earth in 2022. On May 31.21 UTC, the dust trail ejected in 1995 is forecast to approach the Earth as closely as 0.00038 au, in excellent agreement with the study by Lüthen. Image credit: David Asher, adapted from a diagram by Mikiya Sato.

4 Another solution

Our above conclusion would seemingly close the book on the prospects of observing a meteor shower created in the wake of the 1995 break-up of SW 3. Except … there is yet another possibility.

Interestingly, the first investigators to put forward a countering solution (Figure 5) were Lüthen et al. (2001), who forecast that: "Probably the best chance to see an SW3-id display will come in 2022, when we pass the 1995 trail at about only 0.0004 au distance. The display is especially promising: the disintegration of P/SW3 in 1995 should have introduced a lot of dust particles into the trail."

A later independent study (Figure 6) by Horii et al. (2008) buttressed the findings of Lüthen et al. (2001), by indicating that "the dust trail ejected in 1995 will approach the Earth as closely as 0.00038 au … in 2022 meteors due to this dust trail are highly expected."

The obvious question is, what is the cause of this discrepancy? Why does Wiegert et al. and our study show that the fragmented material released by SW 3 in 1995 clearly misses Earth in 2022, while two other studies predict otherwise?

Cometary ejection

In the case of predictions for most meteor showers, it is assumed that the ejection velocity of material shed from the nucleus of the parent comet would be within the range between −30 and +30 m/s, where "+" is in the direction of the body's motion and "−" in the opposite direction. In the case of Vaubaillon's model, the typical ejection velocity considered for a 1-mm sized particle is 20 m/s (± 20 m/s).

In comparing the breakup of comet 3D/Biela to SW 3, the former presumably split either in 1842 or early 1843, near aphelion (Marsden & Sekanina, 1971). That resultant splitting was slow and subtle and was not detected until nearly the end of 1845 and did not contribute to any noticeable increase in the apparent brightness of that comet. It was determined that Biela split with a relative velocity between the two portions of only 1 m/s.

In contrast, the breakup of SW 3 apparently took place in early October 1995, within just a couple of weeks after perihelion on September 22nd. Additionally, the breakup was accompanied by a brightness spike of more than six magnitudes which occurred over just a fortnight in early October 1995, likely due to a sudden and massive expulsion of dust. Horii et al. noted that "... since meteoroids were ejected from the split nuclei of the comet, these meteoroids were likely to have higher ejection velocity than usual." Their study computed an ejection velocity of −26.71 m/s, meaning that the dust was ejected in the opposite direction of the comet's motion.

But there is yet another important factor to consider.

Size matters

That other factor is the size of the ejected particles. In the case of most of the annual meteor showers, the majority of visible meteors are caused by particles generally ranging in size from about that of a small pebble (∼2 mm) down to a grain of sand (∼0.3 mm), and generally weigh less than 1–2 grams.

As is important in understanding the physical break up of a comet nucleus, is that its constituent particles are expected to vary in size from sub/micron-sized flecks of dust to multi-millimeter grains of sand and even larger pebbles and "rocks". How such large particles are spatially distributed depends in part on the spin of the comet's nucleus and the locations of its outgassing regions. Small particles (≤0.1 mm) are pushed away more rapidly by solar radiation pressure regardless of the direction they leave the nucleus, and this pressure of sunlight helps to force such dust particles to a position trailing behind the comet. Larger particles, however, are greatly unaffected by solar radiation pressure.

In Horii et al. (2008), the effects of solar radiation pressure *were not considered*. This combined with negative ejection velocities suggest that large particles from 1995 would preferentially migrate to a position *forward* of the comet, not behind, while smaller particles would be "blown out" from this part of the meteoroid trail.

Lüthen et al. (2001) also did not take solar radiation pressure into consideration with their calculations. In exploring the prospects of meteor activity from four different meteoroid trails shed by SW 3 dating back to 1908, this study considered trails from 1941, 1952 and 1995 which were, "on orbits which radiation pressure cannot assist particles to achieve (occurring at a negative Δa_0[c])."

[c] Δa_0 is defined as the initial difference in semi-major axis after ejection from the comet that allows the nodal crossing to occur at exactly the relevant time in late May or early June of the year in question. The "0" refers to ejection time (i.e., "time zero"), the "a" refers to semimajor axis and the Δ refers to difference from the parent comet. Thus, it is the difference between the meteoroid's semimajor axis and the comet's semimajor axis at the time of ejection. The units are the units of the semimajor axis of an orbit.

The big question of course is, how many large particles can be expected to be ejected with velocities of −26.71 m/s? Typically, not many for most meteoroid trails. Stream modeling predicts the consequences – in terms of observable meteors – for a given distribution of ejection velocities. The implication of the Horii et al. study is that the more particles are ejected at −26.71 m/s (normalized to tangential ejection at perihelion), the greater an outburst will result. Jenniskens (2006) discusses ejection speeds and how they scale with meteoroid size. The required −26.71 m/s is a little on the high side, but not excessively so and moreover we can expect some meteoroids to acquire velocities in excess of the nominal value (Jones, 1995; Brown & Jones, 1998; Jenniskens, 2006).

Put simply, the 1995 trail is rather unique, having been formed in the wake of the major 1995 disruption of SW 3. Based on current knowledge of comet ejection processes, the ejection velocity range from 73P should (just) encompass the required value, for meteoroids of visual meteor size.

Hence the reasons for anticipating a possible meteor outburst in 2022.

Compilation of Earth passages

In Table 2 we compare the predictions of Lüthen et al. (2001) and Horii et al. (2008) for the Earth's encounter in 2022 with the material shed in 1995 by SW 3. The two independently predicted times of encounter with the 1995 trail *differ by only four minutes* and the difference in the distance between the orbit of the trail and the Earth's orbit ($r_E - r_D$) is practically negligible, only 0.00002 au.

The entry velocity (V_g) of the prospective meteors through the Earth's atmosphere is just over 12 km/s in both studies. To this Horii et al. notes that, "... it is a disappointing point that the value of V_g is lower than general meteor showers." As noted by Lüthen et al., "The geocentric velocity V_g (given in km/s) needs to be increased by about 4 km/s for observing purposes due to the gravity of the Earth."

The Leonids are the *swiftest* of all shower meteors, $V_g \approx 72$ km/sec. This is almost the highest theoretical speed for meteors belonging to the solar system due to their head on trajectories relative to Earth's orbit. Contrarily, meteors from SW 3 with $V_g \approx 12.5$ km/sec, would be practically the *slowest* of all known shower meteors. This is due to the fact that they are moving in the same general direction as Earth and must overtake the Earth in their orbit in order to be seen.

Last dance

As previously noted, the Lüthen et al. (2001) and Horii et al. (2008) studies both suggest that in the wake of the 1995 breakup of SW 3, larger meteoric particles were ejected in the direction opposite to the comet's motion. So, while starting out behind the comet, they ultimately may have ended up *moving ahead/forward of the comet* because they are moving in smaller orbits. In this context we repeated our original Dance methodology of creating a meteoroid trail for SW 3 using orbital

Table 2 – Predictions for 1995 trail in 2022.

	Date of encounter	Time (UT)	$r_E - r_D$ (au)	Longitude of node	Trail	V_g (km/s)
Lüthen	2022 May 31	4:55	0.00040	69°.440	1995	12.10
Horii	2022 May 31	4:59	0.00038	69°.448	1995	12.84

elements from 1995, but this time, 19 comets were positioned along a radius vector directed towards the Sun. Starting with the 1995 perihelion distance of SW 3, each comet was again separated incrementally by *decreasing distances from the Sun* of 0.00053789 au or 80,000 km (50,000 miles). A Pace of 1000 and a Zoom of 64× were again utilized.

On 2022 May 31, at 05:00 UTC, Earth was positioned between comet samples #12 and #13 (Figure 7).

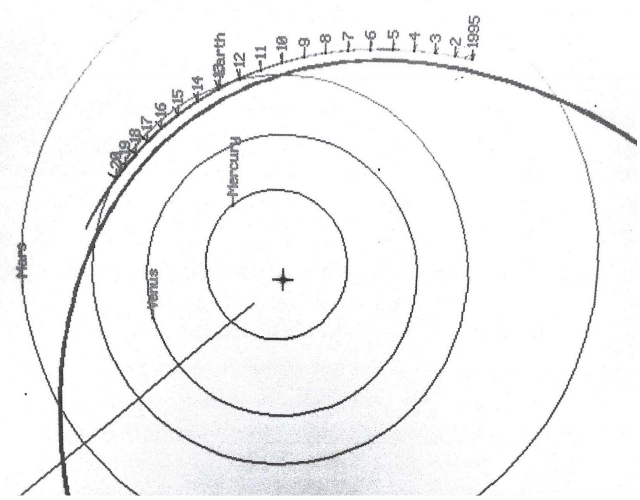

Figure 7 – Positions of Earth, SW 3 and presumed train of meteoroids on 2022 May 31 using Dance of the Planets orbital simulator. Assuming meteoroids are moving *ahead* of the parent comet ("1995"), interaction with the Earth takes place between comet samples #12 and #13. A second computation was then made regarding this particular segment of the train to narrow down the time when meteoroids would be closest to Earth's vicinity. Five comet samples were found, falling within a 2.99-day time frame which encompassed the date and time of maximum ascertained by Lüthen et al. (2001) and Horii et al. (2008).

After the orbital elements were determined for these two cometary proxies, elements for another 18 objects were closely approximated by linear interpolation; these 20 objects would then represent that particular segment of the trail of meteoroids that would come near enough to interact with Earth.

Starting from 2022 May 1, these 20 new objects were set into motion, but this time using a much slower Pace of 100 (in which one minute equates to about 20 months).

In Dance, when a sample comet approaches very close to a planet – in this case Earth ("E") – its orbit may be significantly modified. In this particular case, five out of the 20 comets underwent some degree of perturbation as shown in Table 3 with comet samples 16 through 20: the second column is the Earth-comet distance in Earth radii when the comet sample began to be perturbed. The fourth column is the UTC of least separation, and the fifth column the corresponding distance, again in Earth radii.

The case of comet sample #16 shows least separation occurring only 62 minutes after the mean of Lüthen et al. and Horii et al., while the nearest of these five approaches to Earth (sample #18) comes just 1.49 days prior. So, it would appear that our Dance methodology worked quite well in simulating Earth's 2022 interaction with a meteoroid trail composed of large particles shed by the 1995 break-up of SW 3, and is in good agreement with the findings of both Lüthen et al. and Horii et al.

Intensity/duration "guesstimates"

It is problematic to try and predict meteor rates for a possible 2022 display of SW 3 meteors, primarily because Earth has never interacted with this particular meteoroid trail before. As noted previously, on 2017 May 30–31, between 23:39 and 00:45 UTC, five shower members from SW 3 were captured by NASA Cameras for all-sky meteor surveillance in California (CAMS). Lüthen et al. (2001) had forecast possible activity from a dust trail shed by this comet from 1941; the miss distance ($r_E - r_D$) was considered somewhat large (0.0011 au), yet slight activity was still recorded.

Compared to 2017, $r_E - r_D$ in 2022 is reduced to about one-third, to roughly 0.0004 au. That would suggest, at the very least (from a scalability argument), a potential hourly rate for 2022 of about 14.

However, the impending interaction with the 1995 trail will likely be composed of a far-more dense concentration of debris having been discharged in the wake of the fracturing of SW 3's nucleus compared to the 1941 trail. But just *how much denser*, and what that could ultimately translate to in terms of overall meteor numbers is unknown.

A ten-fold increase would suggest rates of 140 per hour; a strong outburst similar to the annual Geminid or Quadrantid displays, while a one-hundred-fold increase would suggest 1,400 per hour; a full-fledged meteor storm.

It is probably prudent to have conservative expectations and focus on the former, lower rate possibility, although as we are about to see, we certainly cannot discount the latter possibility.

Bielids revisited?

In meteorology, "analog forecasting," (as the technique is called), operates on the straightforward principle of making predictions by comparing current weather patterns to similar patterns (or analogs) from the past. Some call this type of forecasting pattern recognition. The question now arises: Can we use an "analog methodology" to forecast a meteor shower?

Table 3 – Earth interaction with 1995 meteoroid trail from SW 3.

Sample	Pert. dist. Earth radii	Date	UTC of min. distance	Min. dist. Earth radii
E-20	261	2022 May 28	06:11	229.3
E-19	260	2022 May 28	23:52	162.1
E-18	260	2022 May 29	17:06	130.1
E-17	260	2022 May 30	11:23	154.9
E-16	260	2022 May 31	05:59	229.3

Table 4 – Circumstances of 3D/Biela dust trail encounters in 1872 and 1885 compared with the 73P/SW 3 (1995 trail) encounter in 2022.
* ZHR values for 1872 and 1885 are based on an analysis by P. Jenniskens.

Year	Comet	Trail	Δa_0 au	$r_{\rm E} - r_{\rm D}$ au	f_M	ZHR*
1872	3D	4 revolutions	+0.0222	−0.00119	0.249	7400
1885	3D	6 revolutions	−0.0060	−0.00032	0.285	6400
2022	73P	5 revolutions	−0.0220	+0.00039	0.240	????

A study concerning dust trail density and variations of ZHR for past and future Leonid storms (McNaught & Asher, 1999) used three statistical parameters, $r_{\rm E} - r_{\rm D}$, Δa_0 and f_M[d]. But the Leonid parent comet (55P/Tempel-Tuttle) is a "Halley-type" comet with a period of 33 years in a highly-inclined orbit, so we cannot use this comet for a comparison to SW 3.

However as previously mentioned, there was the splitting of the nucleus of comet 3D/Biela in 1842–43, which was followed by spectacular Bielid (or "Andromedid") meteor storms radiating from Andromeda on 1872 November 27 and again in 1885. And like SW 3, 3D/Biela was a member of Jupiter's comet family, with an orbital period of 6.6 years. In the absence of any previous data points (trail encounters) with material that was shed by SW 3 in 1995, then the next best thing is to work by analogy with different streams. In this case, Jenniskens & Vaubaillon (2007) determined that the 1872 and 1885 storms were caused primarily by dust released by 3D/Biela in 1846, with only "minor contributions from dust ejected in 1839 and 1852, respectively." Thus, we decided to concentrate solely on the 1846 dust trail.

In Table 4 we compare the dust trail parameters of the resultant 1872 and 1885 Bielid storms with the upcoming situation for SW 3 in 2022. At first glance, the comparison of the 19th century storms produced by 3D/Biela with the upcoming situation in May 2022 for SW 3 appears supportive for a strong outburst; possibly even a storm.

With similar orbits, the conversion factor from meteoroid ejection speeds to Δa_0 will also tend to be similar. This is relevant since the strength of the outburst depends on the quantity of meteoroids (of a given size, which will correspond to the meteor brightness) at the given Δa_0.

It should be stressed, however, that comet 3D/Biela was brighter (an absolute brightness, pre-splitting, of H_{10} =+7.5 mag. versus +13.2 mag. for SW 3) and its nucleus considerably larger in diameter (∼4 to 6 km[e]) than SW 3. These two factors, unfortunately work against us, probably meaning fewer meteoroids are generated overall by SW 3. And furthermore, the material shed from 3D/Biela congregated *behind* the comet, as opposed to SW 3, where the material shed in the wake of the 1995 fracture of its nucleus, is assumed to be *in the front* of the comet. So, in spite of the similarity of all three dust trail parameters, such a difference in the orbital geometry for the SW3 trail is, unfortunately, not exactly comparable with the two trails cited for 3D/Biela.

Historically, however, there are certainly many other streams, including the Bielids, where $r_{\rm E} - r_{\rm D}$ values of a few earth diameters have yielded outbursts or storms. This and the moderately good f_M provide us with a bit of encouragement.

Sluggish streaks . . . short duration

Once again, there is also the vexing problem of the very slow entry velocity of these meteors through Earth's atmosphere. A large proportion may end up appearing predominately faint (magnitude +4 or +5) or even meteors perceptible only by using radio or radar techniques (>+6). On the other hand, if many of the associated meteoroids end up much larger than normal, that could offset their slow speeds and make for a somewhat bright display. As a comparison, the Bielid/Andromedid meteors of 1872 were described as primarily "slow, faint and evanescent," (Galea, 1995) but some exceeded 1st magnitude, often appearing "red, with trains of orange sparks" (Ottewell, 1989).

Regarding the duration of any potential outburst, like many other similar cases, it is likely to be short-lived, probably lasting on the order of several hours or less, with a sudden commencement and an abrupt end. Observers are urged, however, to watch for any forerunners that might be noted a day or two in advance

[d]Defined as the "mean anomaly factor," it is dust density compared to that in the unperturbed one-revolution dust trail. Or put another way, the ratio of the perturbed to the unperturbed dust density of the dust trail measured averaged over one revolution.

[e]An estimate that we made by comparing other comets with similar absolute brightness. See Hughes (2002).

of the main display; and maybe a straggler or two a day or so afterwards.

5 Radiant, area of visibility, moonlight

Until now, meteors associated with SW 3 have been referred to as "Tau (τ) Herculids." These are most likely directly related to Shibata's 1930 prediction of a possible meteor shower when the Earth passed close to the comet's node. That forecast was based on possible meteoroids *trailing behind* the parent comet.

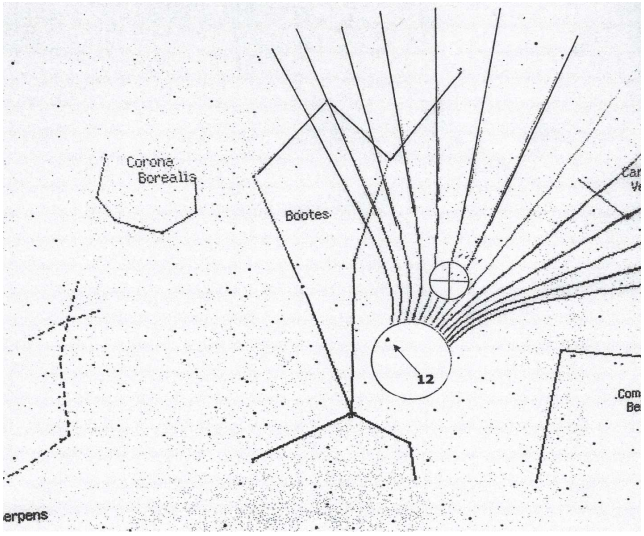

Figure 8 – Position of the radiant (using Dance of the Planets) for a possible meteor outburst near 5^{h} UTC on 2022 May 31 at $\alpha = 210\overset{\circ}{.}17$ $\delta = +25\overset{\circ}{.}03$. Rather than a small patch, it appears that the potential radiant, in the constellation of Boötes could measure several degrees or more in width. An arrow points to the +4.8-magnitude star 12 Boötis. The smaller circle encompassing a cross, is a positional consensus based on our position combined with that of Lüthen et al. (2001) and Horii et al. (2008). This mean radiant position of $\alpha = 208\overset{\circ}{.}35$ $\delta = 27\overset{\circ}{.}45$ is near the border of Boötes and Canes Venatici, less than a couple degrees southeast of the globular cluster Messier 3.

However, our forecast for 2022 is based on meteoroids that are traveling *forward or ahead* of SW 3. The end result is a possible radiant positioned not in Hercules, but within the boundaries of the constellation of Boötes, about 6° north-northwest of Arcturus and very close to the +4.8-magnitude star 12 Boötis (Figure 8). And rather than a small patch of sky, it appears that the potential radiant may measure several degrees or more in width. This may be due in part to the "special circumstances" of this interaction, as well as the low geocentric velocity of this meteor shower, as other similar studies have shown (Sato & Watanabe, 2014).

If so, then any prospective display of SW 3 meteors in 2022 will appear to materialize from a relatively large region of the sky.

Table 5 compares our results to those of Lüthen et al. (2001) and Horii et al. (2008).

Table 5 – Expected position of radiant (J2000.0).

	α	δ
Lüthen	$205\overset{\circ}{.}40$	$+29\overset{\circ}{.}20$
Horii	$209\overset{\circ}{.}48$	$+28\overset{\circ}{.}13$
Rao	$210\overset{\circ}{.}17$	$+25\overset{\circ}{.}03$

As for the region of visibility (Figure 9), a large portion of the contiguous United States, south-central and eastern Canada (including the Maritime Provinces), Mexico, Central America, South America as well as a small slice of West Africa are the regions of the world well positioned for this event. In the U.S. the altitude of the radiant ranges from around 50° in eastern New England to 80° or more in southern California and the Desert Southwest.

Across parts of the Pacific Northwest, northern Rockies and Great Plains, as well as for a slice of the Canadian Prairies, northern Ontario, central Quebec, most of Newfoundland and Labrador, the peak is expected to come during astronomical twilight (Sun 12 to 18° below the horizon), but the sky should still be sufficiently dark for sighting the brighter stars as well as any bright meteors.

Unfortunately, for far western and northern North America, as well as for the rest of the globe, the twilight sky will either be too bright, bathed in sunlight or facing away from any incoming meteors, precluding a view of any possible display.

So far as the situation regarding the Moon, it will arrive at new phase on May 30 (11:30 UTC) and will provide absolutely no interference.

6 Conclusion

In the aftermath of the break-up of the nucleus of comet 73P/Schwassmann-Wachmann 3 in 1995, two possibilities exist: Either the resultant material expelled will completely miss the Earth, or we will have a direct interaction with a swarm of large meteoric particles at the end of May in 2022. Our simulations confirm that both prospects are possible. The former case would result visually in little or nothing being observed. The latter case might possibly result in a prolific display of very slow, bright and colorful meteors. However, because of their slow speed, the meteors could also end up appearing very faint or not visible at all to the unaided eye. Unfortunately, this is all something new, and without knowledge of the exact orbital parameters and physical circumstances, a precise forecast is well-nigh impossible to make.

Such are the difficulties in meteor shower forecasting: At what mass-loss rate and precisely what velocities is a comet releasing debris? Some ejection directions/speeds will provide very efficient delivery of fragmented meteoritic material to Earth while others will not. Comets also are rather erratic in their dust production, jetting, (and break-ups of course) that only complicate matters. Additionally, particles of different sizes, morphologies, and compositions also react differently to the effects from the pressure of sunlight. So, as to exactly what might be expected at around 5^{h} UTC on 2022 May 31 is anyone's guess.

With no Moon, at least we are confident that skies will be dark. But will the meteors be bright?

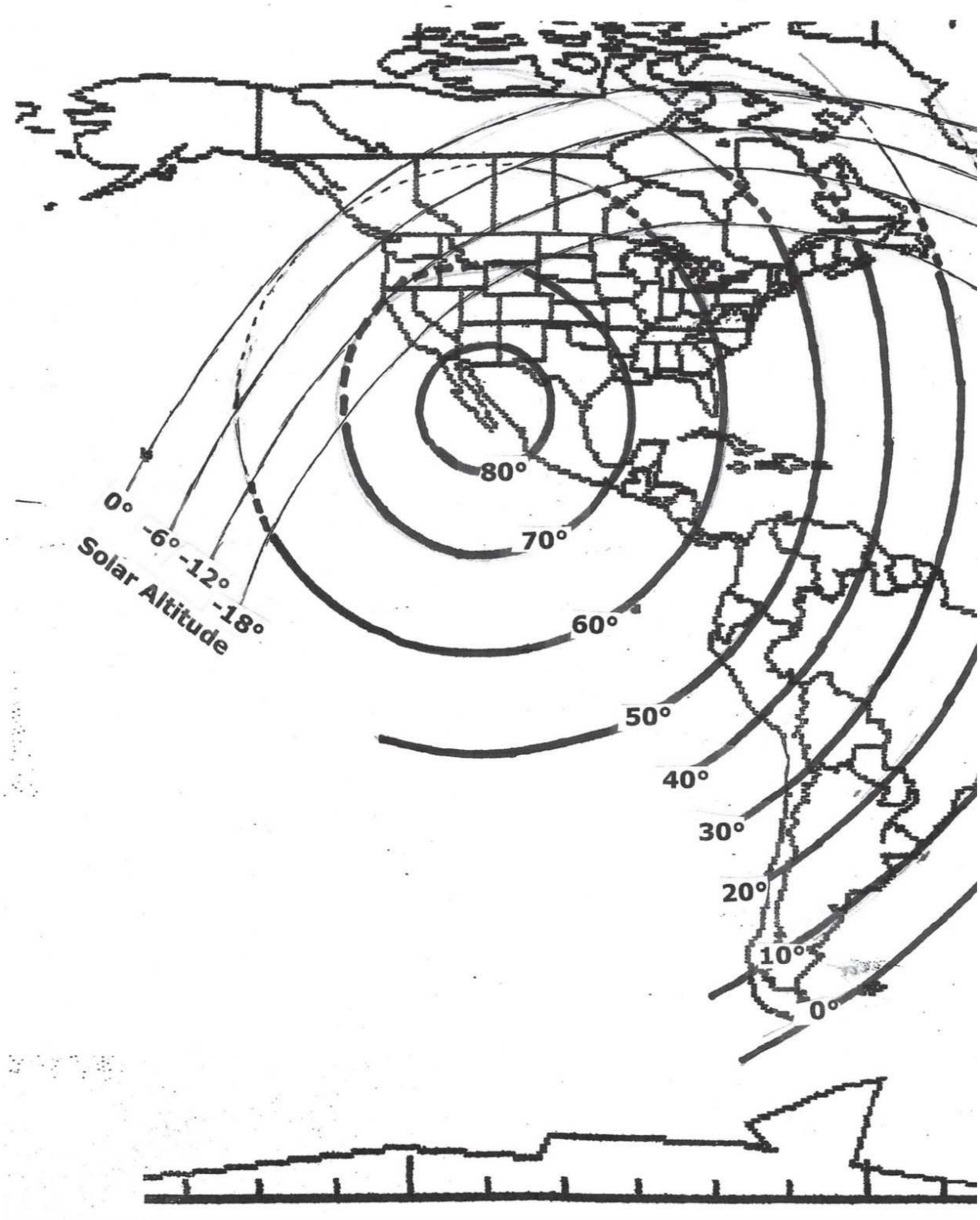

Figure 9 – The map presented here, shows the geographic visibility of the potential meteor outburst and is based on the assumption that peak activity will occur close to 5^{h} UTC on 2022 May 31. Zenithally attracted (apparent) radiant elevations are presented as concentric circles at 10° intervals. Also plotted are zones for civil twilight (Sun 0 to 6° below the horizon), nautical twilight (Sun 6 to 12° below the horizon) and astronomical twilight (Sun 12 to 18° below the horizon). Skies should be dark enough in the astronomical twilight zone to see a fair number of stars as well as any bright meteors. From near the Mexican resort town of Loreto, Baja California Sur, the presumed radiant will be at, or very close to the zenith. In contrast, from southernmost Chile and Argentina, as well as a slice of westernmost Africa (not pictured here), the radiant will be less than 10° above the horizon, likely resulting in true Earth grazers; very long-pathed meteors moving parallel to the Earth's surface. Radio and radar observations are possible from any location on the map (save for Antarctica) at the predicted peak time.

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