Model Predictions for the 2025 October Draconid Outburst

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ABSTRACT

The October Draconid meteor shower, produced by comet 21P/Giacobini–Zinner, is notorious for rare but intense outbursts, some exceeding rates of $\sim 10^4$ meteors per hour. In 2025, Earth will encounter young trails ejected by the comet in 2005 and 2012, producing a meteor outburst and providing a rare opportunity to probe their structure and benchmark meteoroid stream models. We present predictions from three independent dynamical models (NIMS, MSFC, Sisyphus), calibrated against updated activity profiles including the newly observed 2019 and 2024 outbursts. All simulations predict enhanced activity on 2025 October 8, dominated by faint meteors ($m < 10^{-5}$ kg; +4 mag and fainter) primarily detectable by radar. Our best estimate is a radar outburst near 15:00–16:00 UT, driven mainly by the 2012 trail with a possible minor contribution from 2005. The 2025 Draconids may represent one of the strongest radar dominated outbursts of the decade. Coordinated observing campaigns, especially radar measurements across the Northern Hemisphere and optical coverage from Asia, will be essential to validate these forecasts, constrain the dust environment of comet 21P, and improve future predictions of young meteoroid trails.

Key words: meteorites, meteors, meteoroids – comets: individual: 21P/Giacobini–Zinner – methods: numerical

1 INTRODUCTION

The October Draconid (009 DRA) meteor shower is an episodic annual shower active around October 9. Most years it is weak, with Zenithal Hourly Rates (ZHR) below 1, but on occasion it produces spectacular outbursts and storms reaching hundreds to thousands of meteors per hour (e.g., Watson 1934; Lovell et al. 1947; Kresak & Slancikova 1975; Ye et al. 2014). The most dramatic storms in 1933 and 1946 reached ZHRs near 10^4 (Jenniskens 2006), and early studies revealed the meteoroids to be among the weakest known (Jacchia et al. 1950; Borovička et al. 2007).

The Draconid stream shows clear evidence of mass segregation, with a mass index that varies strongly both between apparitions and with solar longitude (Vida et al. 2020). Some outbursts have been detected almost exclusively by radar (e.g., 1999 and 2012; Campbell-Brown et al. 2021), complicating comparisons between instruments and suggesting that past radar-dominated events may have gone unnoticed. A striking example is the 1999 outburst, only identified two decades later in archival radar data (Egal et al. 2019). The unpredictability and occasionally high fluxes of the Draconids, combined with the difficulty of their instrumental detection, make this shower a noteworthy hazard to spacecraft (Moorhead et al. 2025).

The parent body of the Draconids, comet 21P/Giacobini–Zinner, is a Jupiter-family comet with a radius of 1–2 km (Leibowitz & Brosch 1986; Singh et al. 1997; Lamy et al. 2004; Pittichová et al. 2008). Its orbital evolution over the past two centuries has been unusually chaotic (Marsden & Sekanina 1971), with multiple close encounters with Jupiter substantially altering the orbit, including one in 1898 that preceded its discovery (Vaubaillon et al. 2011). In addition, 21P has shown abrupt changes in nongravitational forces, including a marked shift between its 1959 and 1965 apparitions (Yeomans & Chodas 1989; Sekanina 1985; Ehlert et al. 2019).

The comet's chaotic orbital history, combined with the observational challenges of the Draconid shower, makes accurate forecasting difficult. Even with large-scale dynamical simulations, predicting shower intensity remains uncertain, particularly for radar-dominated outbursts of small particles (Egal et al. 2019). The 2025 return offers a timely opportunity to test model performance against well-constrained recent apparitions. In this work, we present new forecasts based on three independent stream models, calibrated with updated activity profiles, including the newly measured 2019 and 2024 outbursts. Our modeling approach is described in Section 2, observational constraints in Section 3, and predictions for 2025 are provided in Section 4.

2 STREAM MODELS

We applied three independent meteoroid stream models to forecast the 2025 Draconid return: NIMS, MSFC, and Sisyphus. In all cases, the simulations follow dust released by comet 21P and identify Earth-approaching particles. Potential impactors were retained if they crossed the ecliptic plane within a distance ΔX and a time ΔT

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of Earth's position, and were then used to generate simulated activity profiles for comparison with observations. Each model applied this common framework with distinct assumptions for the comet's ephemerides and particle ejection, as described below.

(i) The Numerical Integration of Meteoroid Streams (NIMS; Egal et al. 2019) simulates dust released by comet 21P since the mid-19th century. A total of 14.42 million particles were ejected using the model of Crifo & Rodionov (1997), spanning sizes from ∼100 μm to 10 cm and assuming a density of 300 kg m^{-3} (Borovička et al. 2007). Their subsequent motion was integrated under planetary perturbations and radiation forces. Potential impactors were retained if they crossed the ecliptic plane within ΔX = 0.008 au and ΔT = 10 days of Earth's position. Particles were weighted according to the comet's dust production profile measured in 2018 (Egal et al. 2019), following the procedure of Egal et al. (2020). For the first time, separate modelled activity profiles were generated for radar-detectable meteors (+4 to +8 mag) and for optical meteors (brighter than +6 mag).

(ii) The NASA MSFC Meteoroid Stream Model (MSFC; Moser & Cooke 2004; Moser & Cooke 2008) simulates dust production by comet 21P since 1608. A total of 336 million particles were ejected following the model of Jones & Brown (1996), with sizes between ∼100 μm and 10 cm and a density of 1000 kg m^{-3}. Particles were integrated under gravitational and radiation forces, and those approaching Earth within ΔX = 0.01 au and ΔT = 7 days were selected for analysis.

(iii) The Sisyphus model (this work) focuses on trails released during the 2005 and 2012 perihelion passages. For each passage, 10,000 meteoroids of assumed density 300 kg m^{-3} were ejected using the velocity distribution of Brown & Jones (1998). Their motion was integrated under planetary perturbations and radiation forces. Meteoroids were considered part of the 2025 Draconid shower if they passed Earth with ΔT = 7 days and ΔX = 0.02 au.

The chaotic orbital history of comet 21P, including a close encounter with Jupiter in 1898 and limited pre-1966 astrometry (Vaubaillon et al. 2011; Yeomans & Chodas 1989), prevents direct long-term integration from present-day elements. To address these uncertainties, the ephemeris of each apparition was computed by integrating the comet's motion forward or backward from the nearest accurate orbital solution available for that epoch, rather than from the most recent orbit. We used JPL Horizons[1] orbital solutions spanning 1900–2017 (SAO series for 1900–1998; K054/18 for 2006; K123/6 for 2013; K253/3 for 2017). For the Sisyphus model, we adopted the DE440 ephemerides, with initial conditions and non-gravitational parameters for 21P obtained from JPL CNEOS at JDE 2458064.5 (7 Nov 2017).

Despite the large number of simulated particles, only a small fraction approach Earth's orbit within the critical distance ΔX near the time of the shower (e.g., Egal et al. 2019). To address this, the ΔT parameter is introduced as an along-track uncertainty, effectively broadening each particle into a swarm of clones spread across $\pm\Delta T$ at its node and thereby increasing the number of retained impactors.

Restrictive selection criteria are necessary to capture the perturbed structure of the stream, but they inevitably reduce the statistical robustness of the forecasts. In this work, the $\Delta X, \Delta T$ values adopted for each model were chosen to reproduce the timing and intensity of well-constrained past Draconid outbursts (e.g. Section 3 for NIMS), and are consistent with thresholds successfully applied to streams from both Halley-type and Jupiter-family comets (e.g. Egal et al. 2020; Egal et al. 2023).

[1] https://ssd.jpl.nasa.gov/horizons, accessed June 2024

3 CALIBRATION WITH PAST DRACONID ACTIVITY

3.1 Observations

The observational characteristics of Draconid outbursts between 1926 and 2018 were summarized by Egal et al. (2019). Since its discovery, the shower has produced four historic storms (1933, 1946, 1999, 2012) and several major outbursts (1985, 1998, 2005, 2011, 2018, 2019), separated by years of negligible activity.

Systematic radar measurements became available only after 1998 (Campbell-Brown et al. 2021). Since 2002, the CMOR radar has provided a nearly continuous and internally consistent dataset of Draconid activity. Revised flux computations by Campbell-Brown et al. (2021) substantially altered the reported intensities of several outbursts, underscoring the large uncertainties in radar flux determination (potentially up to a factor of twenty for the Draconids, cf. Moorhead et al. 2024). Flux calibration is further complicated by the shower's highly variable mass index, which changes not only between apparitions but also during individual events (Vida et al. 2020; Campbell-Brown et al. 2021).

Figure 1 presents activity profiles from multi-instrument observations of all Draconid apparitions with significant flux enhancements since 1933. While radar data provide the only record of several outbursts (e.g., 1999, 2012, 2019), others (1998, 2011, 2018) were simultaneously observed with visual, optical, and radar techniques. Direct comparison reveals systematic offsets in peak timing (up to 30–45 minutes between optical systems) and discrepancies between optical and radar maxima, underscoring the importance of coordinated multi-instrument campaigns.

Two additional outbursts expand the record since 2018. In 2019, enhanced radio activity was detected by the Mohe radar and by CMOR, which measured an equivalent ZHR of ∼625 (s = 1.8) at SL 194.734° (Li et al. 2022). The smaller sub-peak near SL 194.56 detected in CMOR data is most likely caused by noise and is not present in the independent measurements of Li et al. (2022). The main peak, detected by both systems, is in excellent agreement with predictions by Egal et al. (2019). On 2024 October 8, a weak unanticipated outburst was detected. GMN reported a peak ZHR of ∼16 hr^{-1} at SL 195.08 ± 0.05° (Vida et al. 2024), while Japanese radio and CMOR data indicated maxima about 45 minutes earlier and an hour later, respectively (Rendtel et al. 2024).

3.2 Calibration

Our NIMS simulations were calibrated against the major outbursts shown in Figure 1. For most apparitions, peak timing was reproduced within ∼30 minutes, and modeled fluxes were consistent with observations for six returns (1933, 1946, 1985, 1998, 2011, 2019). The weak 2024 enhancement was also reproduced, predicted about one hour earlier than the GMN optical maximum (Vida et al. 2024) but in good agreement with radio measurements (Rendtel et al. 2024).

Three returns (1999, 2012, 2018) proved more difficult to reproduce, though the results remain within observational uncertainties. Modeled fluxes diverged by factors of 2–8 depending on the dataset, reflecting substantial measurement challenges: the 1999 rates relied on a precursor radar with uncertain calibration (Campbell-Brown et al. 2021); the 2012 storm was produced by a trail ejected shortly after a major orbital alteration of 21P; and the 2018 outburst exhibited complex filamentary structure and rapid mass index variations (s shifting from 1.74 to 2.32 within minutes; Vida et al. 2020). The 2005 return was missed entirely, as particles from the 1946–1953 trails were displaced beyond Earth's orbit and excluded by our tight ΔX criterion.

Attempts to tune the model to these four apparitions degraded the fits for other years, underscoring the challenge of achieving a uniform calibration across the shower's history. Given the uncertainty in radar flux measurements (Moorhead et al. 2024), we prioritized reproducing peak timing and intensity of the well-constrained outbursts over over calibrating to the uncertain cases. With this approach, the NIMS model reproduces the timing and structure of most Draconid outbursts and provides a consistent baseline for forecasting 2025.

4 2025 FORECAST

Figure 2 shows the predicted 2025 activity from the NIMS, MSFC, and Sisyphus models. We find that the trails ejected by comet 21P in 2005 and 2012 approach Earth's orbit on October 8-9, together with more dispersed particles from earlier apparitions. Even with similar integration parameters, the models yield noticeably different trail structures and elongations. Depending on the adopted ejection and selection criteria, the 2005 trail either intersects Earth (MSFC and Egal et al. 2019), producing minor activity, or passes slightly beyond Earth's orbit (NIMS and Sisyphus). The denser 2012 trail is offset from Earth in most models, but lies close enough that activity cannot be ruled out. Indeed, the 1966 trail was similarly offset in 2012, yet produced a radio storm of ~3000 meteors h^{-1} (Ye et al. 2014; Campbell-Brown et al. 2021). The predicted activity is therefore highly sensitive to the adopted ejection model and the $(\Delta X, \Delta T)$ selection parameters. Our best estimate, calibrated against as many past outbursts as possible, is shown in Figure 2.

All three models predict enhanced activity on October 8. NIMS yields a radar outburst of ~400 meteors h^{-1} at $\lambda_\odot = 195.26°$ (15:20 UT), dominated by the 2012 trail with an earlier, smaller contribution from 2005. MSFC results agree in timing and relative strength, also indicating dominance by sub-mm particles (masses $< 10^{-6}$ kg) and hence radar-dominated activity. By contrast, the Sisyphus model favors a slightly earlier peak at $\lambda_\odot = 195.18$–$195.23°$, produced by mm–cm particles from the 2012 and 2005 trails. Interpreting Sisyphus rates (meteors per 10 000 km^2 per hour) as a ZHR proxy gives modest radar activity (ZHR_{eq} ~90) and lower visual rates near 25 h^{-1}.

A comparison with other forecasts is given in Table 1. Most simulations predict enhanced radio activity from the 2012 trail on 2025 October 8, between 15:00–16:00 UT, with a possible 2005 contribution depending on meteoroid selection. The Egal et al. (2019) and NIMS predictions give the highest expected rates, while others suggest lower activity. The contribution of individual trails remains highly sensitive to the adopted $(\Delta X, \Delta T)$, emphasizing the importance of 2025 observations for constraining future forecasts. The peak is expected during daytime in Europe and North America, making optical observations most favorable from Asia, while radio measurements across the Northern Hemisphere will be critical.

Since the activity is expected to be dominated by faint meteors, enhanced video and telescopic techniques will be particularly valuable. Such systems can extend sensitivity beyond the naked-eye limit and help bridge the gap between optical and radar observations, providing more robust constraints on the shower's mass distribution. Unfortunately, optical observations may be hindered by the full Moon occurring the day prior to the peak, on October 7.

5 CONCLUSIONS

Our simulations indicate that the October 8, 2025, Draconid return is likely to produce a moderate to strong radio outburst, primarily originating from the dust trail ejected by comet 21P/Giacobini-Zinner in 2012. A minor contribution from the 2005 trail and/or mm–cm sized particles is also possible. While all models predict enhanced activity on October 8, the exact timing and relative strength of the peaks differ significantly, underlining the sensitivity of the forecasts to the adopted ejection models and particle selection criteria.

These differences highlight two priorities for improving future forecasts: (1) refining the ephemeris of comet 21P to reduce uncertainties in the nodal-crossing location of the stream, and (2) obtaining more reliable Draconid flux measurements through coordinated multi-instrument observing campaigns, with particular emphasis on accurately determining the shower's mass index.

The 2025 return offers a particularly valuable opportunity to test and validate both the ejection model and the particle selection parameters. The predicted activity originates from young trails with well-constrained cometary apparitions, enabling a more direct comparison between model predictions and observations. Although the peak occurs during daytime in Europe and North America, it will be observable under night-time conditions in Asia and detectable with radio instruments across the Northern Hemisphere. High-quality measurements in 2025 will thus be crucial both for advancing our understanding of the Draconid stream and for benchmarking future forecasts.

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DATA AVAILABILITY STATEMENT

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

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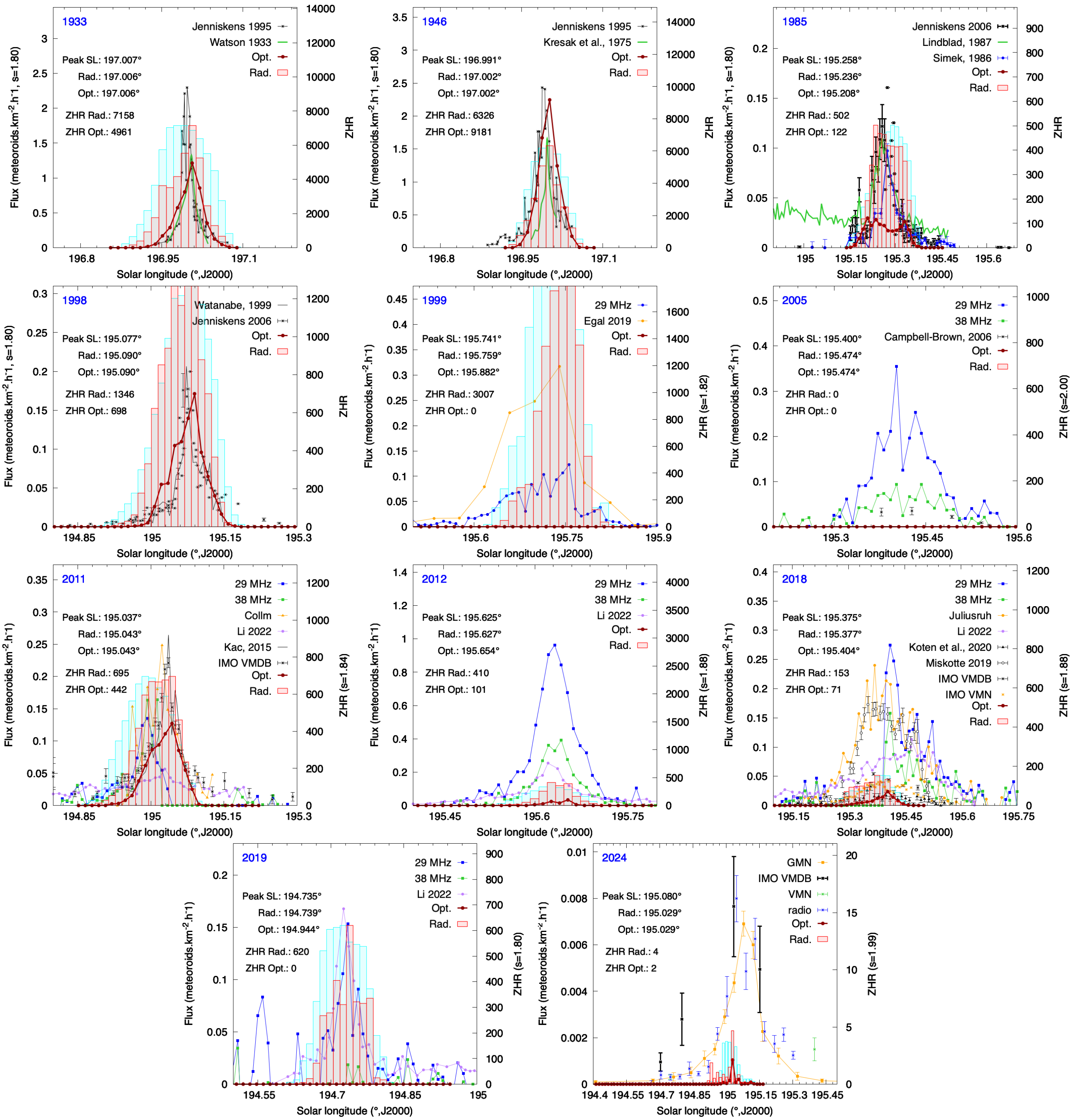

Figure 1. Postdiction of the main Draconid outbursts using NIMS. The weighted simulated activity profile for meteoroids producing meteors detectable at modern optical instrument sensitivities (solid red curve) and in the radar range (red boxes) are compared with visual, optical, and radio observations for each apparition. Observations reported in the literature are shown with their associated reference. Flux profile measurements by CMOR using either the 29 or 38 MHz radar system are also shown where such data are available. ZHR to flux conversion used the mass index s shown in each panel, or the default value $s = 1.80$ from (Campbell-Brown et al. 2021). The raw simulated profile, obtained with minimal weighting and without calibration of the particle size distribution at ejection, is shown in cyan. For each plot, the observed peak solar longitude (Peak SL), along with the simulated time of maximum at radar sizes (Rad) and optical sizes (Opt) and the corresponding ZHR, are indicated. The flux is given to an equivalent Draconid peak magnitude of +6.5 which corresponds to a particle mass of 10^{-6} kg.

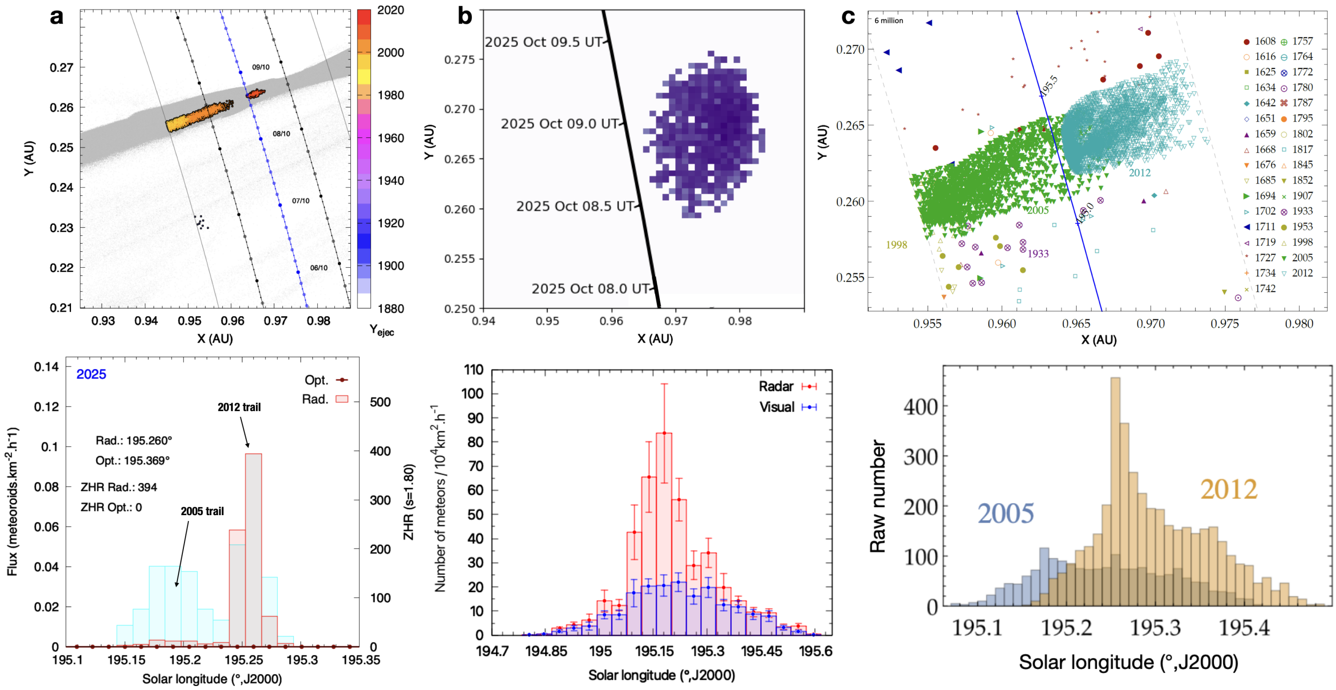

Figure 2. Simulated nodal-crossing locations of Draconid particles (top) and activity profile of the predicted 2025 outburst (bottom), using the NIMS (a), Sisyphus (b), and MSFC (c) models. Only particles crossing the ecliptic plane within the selection criteria (ΔX, ΔT) from Earth's position are shown in color. Particles released by comet 21P in 2005 and 2012 are shown separately in NIMS and MSFC simulated profiles.

Modeller	Trail	SL (°)	Time (Oct. 8)	ZHR	Source
Maslov	2012	195.238	15:07	100-150	Rendtel et al. (2025)
	1907-1953	194.663-195.053	01:07-10:36	<50-60	Maslov (2025)
Ye	1933	195.0	09:19	<2018 rates	Ye et al. (2014)
Vaubaillon	2012	195.269	15:52	<50	Rendtel et al. (2025)
	2005	195.272	15:56	negligible	Rendtel et al. (2025)
Sato	2012	195.257	15:34	-	Rendtel et al. (2025)
Egal	2012	195.252	15:27	950*	Egal et al. (2019)
	2005	195.178	13:39	950*	Egal et al. (2019)
	2012	195.256	15:32	400*	This work, NIMS
	2005	195.185	13:49	400*	This work, NIMS
Moser	2012	195.255	15:31	-	This work, MSFC
	2005	195.175	13:34	-	This work, MSFC
	2005 & 2012 fit	195.264	15:45	-	This work, MSFC
Wiegert	2005	195.18/195.22	13:42/14:40	45/12	(radar/visual), This work, Sisyphus
	2012	195.18/195.14	13:42/12:43	35/13	(radar/visual), This work, Sisyphus

Table 1. 2025 Draconid forecasts performed by independent modelers. All the predicted activity is expected to occur on October 8, 2025. *: ZHR estimate based on the combined activity from the 2005 & 2012 trails.

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