Interstellar Visitors to our Solar System

Collated by John I Davies and Gill Norman

With 3I/ATLAS continuing to dominate some of the astronomical news, we have featured a roundup of some of the latest research surrounding these cosmic callers.
As mentioned in the editorial of this issue, the significant press coverage does serve to raise awareness of the entire field of research. It sparks debate and enthusiasm in the subject, albeit with an inevitable helping of sensational internet claims...

The interstellar object significance scale (Loeb Scale): astronomical classification of interstellar objects

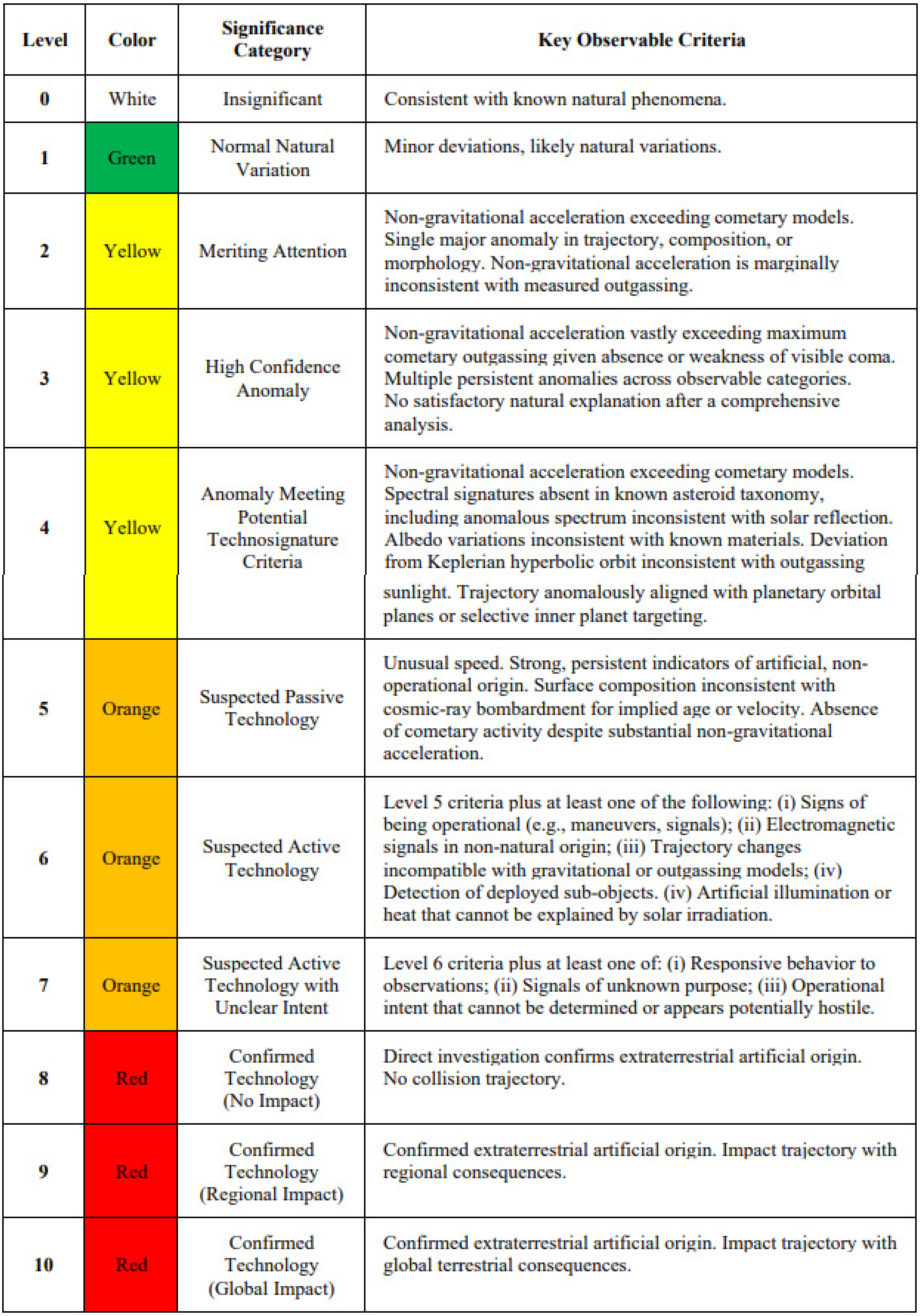
Omer Eldadi, Gershon Tenenbaum (Reichman University, Israel)
Abraham Loeb (Harvard University, USA)

The Vera C Rubin Observatory is expected to increase interstellar object (ISO) detections from a few over the past decade to potentially one per few months, demanding a systematic classification scheme. In this paper, the authors present the *Interstellar Object Significance Scale* (IOSS), also known in the literature as the Loeb Scale [1], a 0–10 classification system extending the proven Torino Scale framework, to address ISOs' unique anomalies, including potential technosignatures. The scale provides quantitative thresholds for natural phenomena (Levels 0–3) and graduated protocols for increasingly anomalous characteristics (Levels 4–7), with Levels 8–10 reserved for confirmed artificial origin. Each level specifies observable criteria and response protocols. They demonstrate the scale's application using 1I/'Oumuamua (Level 4), 2I/Borisov (Level 0) and 3I/ATLAS (Level 4) as test cases. The IOSS provides the astronomical community with a standardized framework for consistent, evidence-based and dynamic evaluation while maintaining scientific rigour across the full spectrum of possibilities as we enter an era of routine ISO encounters. The paper can be viewed here: https://arxiv.org/pdf/2508.09167v1.

See overleaf for the graphic of the Loeb Scale.

[1] The idea for this scale was originally suggested in an essay written by A Loeb in July 2025, https://avi-loeb.medium.com/the-visionary-letter-from-congresswoman-anna-paulina-luna-to-nasa-regarding-3i-atlas-ddb56dce69f0

The Loeb Scale Classification Levels
Credit (graphic and caption): Eldadi et al, Table 1

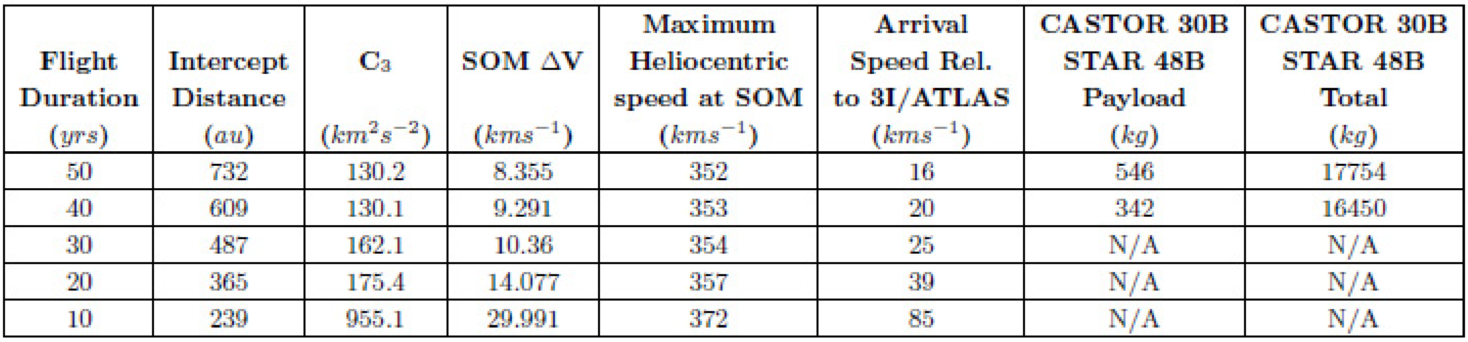


Level	Color	Significance Category	Key Observable Criteria
0	White	Insignificant	Consistent with known natural phenomena.
1	Green	Normal Natural Variation	Minor deviations, likely natural variations.
2	Yellow	Meriting Attention	Non-gravitational acceleration exceeding cometary models. Single major anomaly in trajectory, composition, or morphology. Non-gravitational acceleration is marginally inconsistent with measured outgassing.
3	Yellow	High Confidence Anomaly	Non-gravitational acceleration vastly exceeding maximum cometary outgassing given absence or weakness of visible coma. Multiple persistent anomalies across observable categories. No satisfactory natural explanation after a comprehensive analysis.
4	Yellow	Anomaly Meeting Potential Technosignature Criteria	Non-gravitational acceleration exceeding cometary models. Spectral signatures absent in known asteroid taxonomy, including anomalous spectrum inconsistent with solar reflection. Albedo variations inconsistent with known materials. Deviation from Keplerian hyperbolic orbit inconsistent with outgassing sunlight. Trajectory anomalously aligned with planetary orbital planes or selective inner planet targeting.
5	Orange	Suspected Passive Technology	Unusual speed. Strong, persistent indicators of artificial, non-operational origin. Surface composition inconsistent with cosmic-ray bombardment for implied age or velocity. Absence of cometary activity despite substantial non-gravitational acceleration.
6	Orange	Suspected Active Technology	Level 5 criteria plus at least one of the following: (i) Signs of being operational (e.g., maneuvers, signals); (ii) Electromagnetic signals in non-natural origin; (iii) Trajectory changes incompatible with gravitational or outgassing models; (iv) Detection of deployed sub-objects. (iv) Artificial illumination or heat that cannot be explained by solar irradiation.
7	Orange	Suspected Active Technology with Unclear Intent	Level 6 criteria plus at least one of: (i) Responsive behavior to observations; (ii) Signals of unknown purpose; (iii) Operational intent that cannot be determined or appears potentially hostile.
8	Red	Confirmed Technology (No Impact)	Direct investigation confirms extraterrestrial artificial origin. No collision trajectory.
9	Red	Confirmed Technology (Regional Impact)	Confirmed extraterrestrial artificial origin. Impact trajectory with regional consequences.
10	Red	Confirmed Technology (Global Impact)	Confirmed extraterrestrial artificial origin. Impact trajectory with global terrestrial consequences.

Catching 3I/ATLAS Using a Solar Oberth

Adam Hibberd (i4is, London)
T Marshall Eubanks (Space Initiatives Inc, USA)
Andreas Hein (i4is Exec Director and University of Luxembourg)

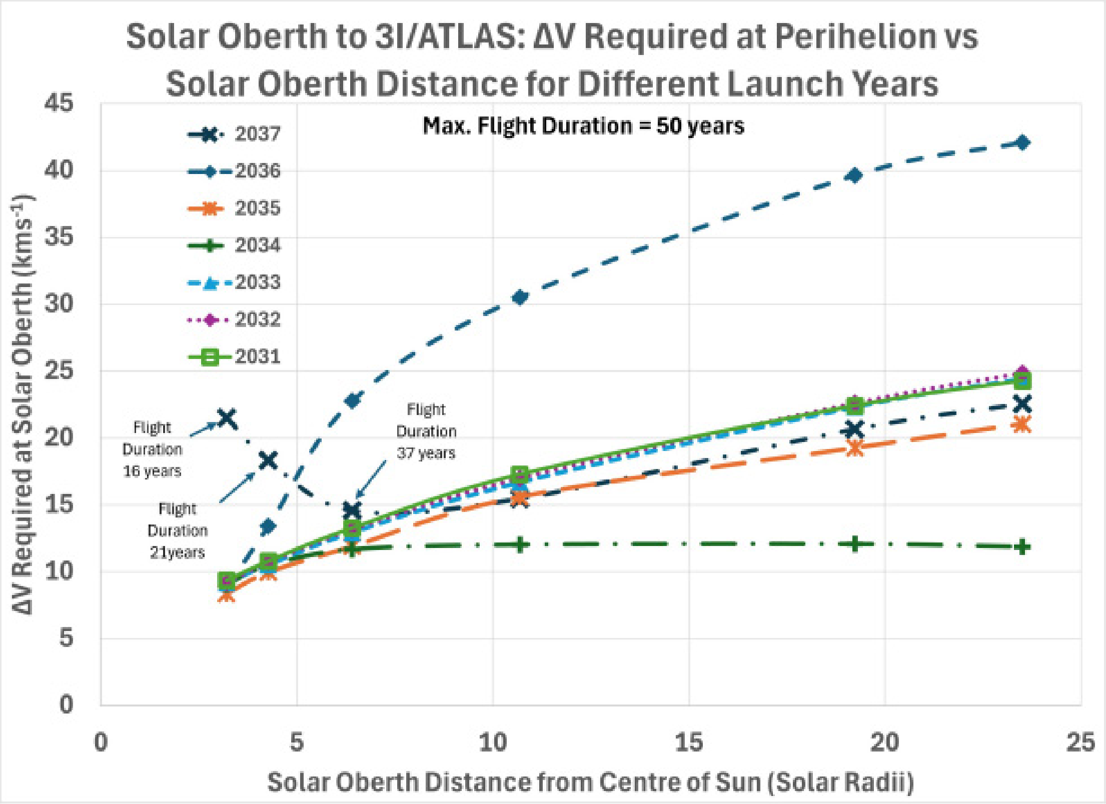
Three of our regular contributors have co-authored this 3I/ATLAS paper; view it here: https://arxiv.org/abs/2601.02533. The third interstellar object to be discovered, 3I/ATLAS, has a unique and continually unfolding story to tell of its nature and origin as it is monitored by telescopes on Earth, orbiting Earth and around the Solar System. Previous research into missions using chemical propulsion have only really addressed the direct case, where the opportunity to launch already expired before 3I/ATLAS's discovery. In contrast, investigations herein exploit 'Optimum Interplanetary Trajectory Software' to simulate an alternative indirect option for chemical propulsion, namely the Solar Oberth Manoeuvre (SOM). For a SOM, a low perihelion burn provides maximum benefit from the Oberth Effect and accelerates the spacecraft rapidly towards the receding 3I/ATLAS. Though in principle feasible, results indicate this option presents significant challenges. For possible launch years between 2031 and 2037 inclusive, a 2035 launch permits the most efficient transfer to 3I/ATLAS. The reference mission requires a SOM at 3.2 Solar Radii from the Sun's centre, with an intercept after 35-50 years. It is found the SOM can leverage spacecraft masses up to approximately 500 kg. Two or three solid propellant boosters could deliver the required SOM ΔV, and furthermore a refuelled Starship Block 3 in LEO has sufficient performance for such a mission. As inevitable with a SOM, some of the payload mass would be needed for a heat shield to protect against the high solar flux at low perihelion.



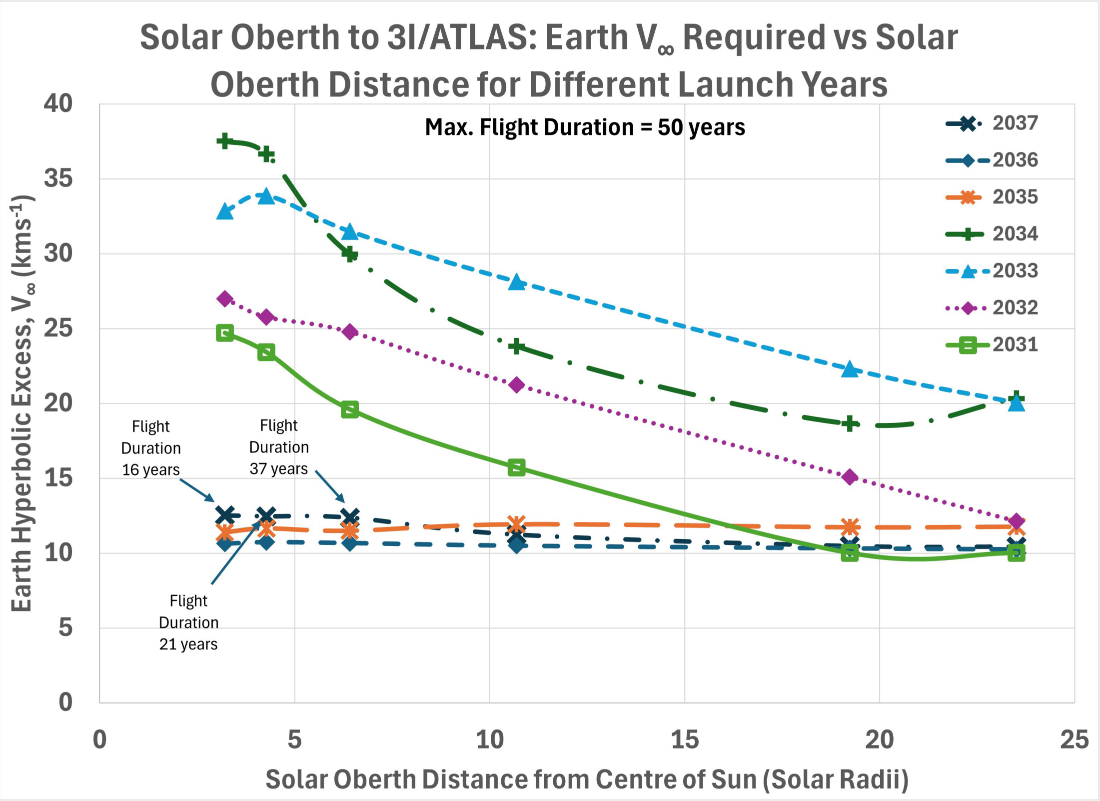
Flight Duration (yrs)	Intercept Distance (au)	C_3 (km^2s^{-2})	SOM ΔV (kms^{-1})	Maximum Heliocentric speed at SOM (kms^{-1})	Arrival Speed Rel. to 3I/ATLAS (kms^{-1})	CASTOR 30B STAR 48B Payload (kg)	CASTOR 30B STAR 48B Total (kg)
50	732	130.2	8.355	352	16	546	17754
40	609	130.1	9.291	353	20	342	16450
30	487	162.1	10.36	354	25	N/A	N/A
20	365	175.4	14.077	357	39	N/A	N/A
10	239	955.1	29.991	372	85	N/A	N/A

Table of possible mission flight durations for a launch year 2035 and with a SOM burn at 3.2SR (Solar Radii) from the centre of the Sun
Credit (graphic and caption): Hibberd et al, Table 1

We are pleased to report that this article has has been accepted for publication in the *Journal of the British Interplanetary Society* and has achieved considerable other external publicity, for example, being featured on Universe Today: https://www.universetoday.com/articles/a-new-concept-for-catching-up-with-3iatlas



1 ΔV needed at SOM against perihelion distance for missions with E-J-SOM-3I sequence and assuming no ΔV at Jupiter
Credit (graphic and caption): Hibberd et al, Figure 1

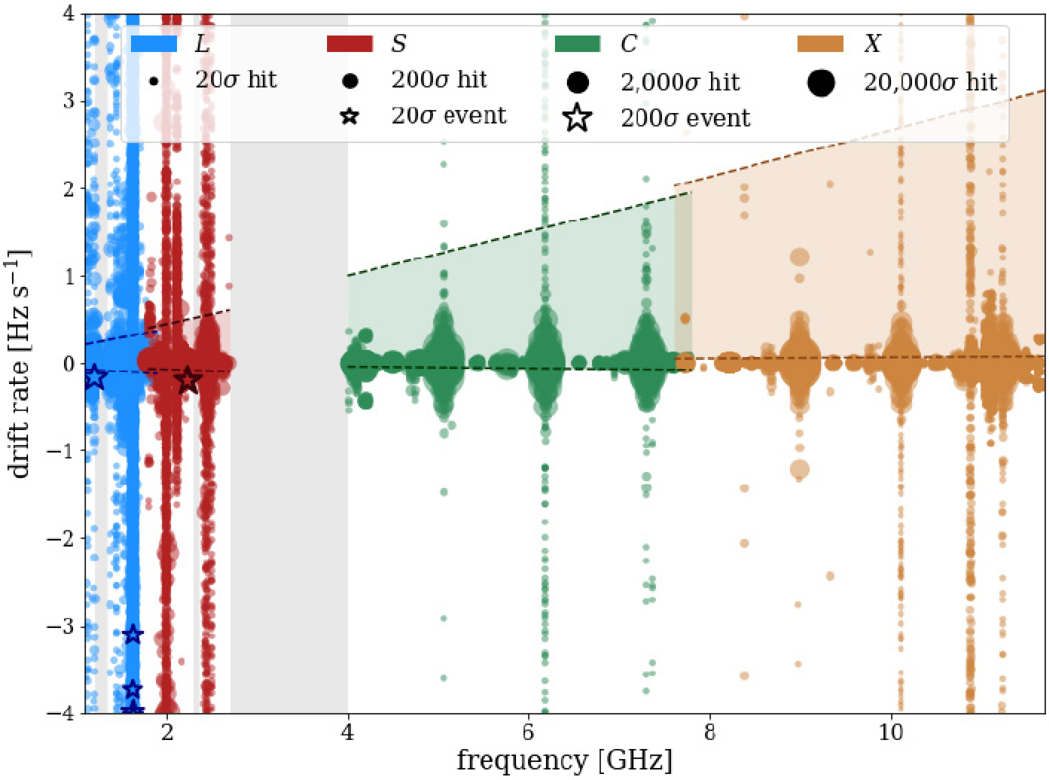


Earth hyperbolic excess speed, v_∞ against perihelion distance needed for missions with the E-J-SOM-3I sequence and assuming no ΔV at Jupiter.
Credit (graphic and caption): Hibberd et al, Figure 2

Breakthrough Listen Observations of 3I/ATLAS with the Green Bank Telescope at 1–12 GHz

Ben Jacobson-Bell (University of California, USA) et al

3I/ATLAS (also designated C/2025 N1 (ATLAS) and, formerly, A11pl3Z) is the third interstellar object (ISO), following 1I/'Oumuamua and 2I/Borisov, to be discovered during a passage through the Solar System. Unlike 1I/'Oumuamua, 3I/ATLAS exhibits mostly typical cometary characteristics (S Deen et al 2025 [1]), including a coma and an unelongated nucleus. There is currently no evidence to suggest that ISOs are anything other than natural astrophysical objects. However, given the small number of such objects known (only three to date), and the plausibility of interstellar probes as a technosignature (eg R A Freitas & F Valdes 1985 [2]), thorough study is warranted (see J R A Davenport et al 2025 [3]).



Distribution of hits (circles) and events (stars) over frequency and drift rate. The marker size gives the S/N. The gray-shaded regions show ranges not sampled, including narrow notch filter regions in the L and S bands. The colour-shaded regions give the range of drift rates expected from Earth's orbital motion and rotational motion and 3I/ATLAS's rotation at each of the four observing bands. These regions do not perfectly align between bands due to 3I/ATLAS's radial acceleration changing during overhead time between observations. No events lie in the expected drift rate regions. Credit (graphic and caption): Jacobson-Bell, Figure 1

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[1] S Deen, R Wainscoat, J Silva, et al. 2025, *Central Bureau Electronic Telegrams*, 5578, 1

[2] R A Freitas, Jr and F Valdes, 1985, *Acta Astronautica*, 12, 1027, doi: 10.1016/0094-5765(85)90031-1

[3] J R A Davenport, S Z Sheikh, S Croft, et al, 2025, doi: 10.48550/arXiv.2508.16825

Putative nonanthropogenic interstellar probes are likely to communicate via narrowband radio signals for transmission efficiency and for the low extinction of such signals across interstellar space; all of humanity's spacecraft, including the now-interstellar craft Voyager 1 and Voyager 2, communicate via such signals. The Breakthrough Listen (BL) programme observed 3I/ATLAS using the 100-m Robert C Byrd Green Bank Telescope (GBT) on UT 2025 December 18, ~1 day before the ISO's closest approach to Earth. Similar technosignature searches have recently been undertaken by S Z Sheikh et al (2025) [1] and D J Pisano et al (2025) [2] over different frequency ranges and with different sensitivities. Like those searches, the authors find no credible detections of narrowband radio technosignatures originating from 3I/ATLAS. View the paper here https://seti.berkeley.edu/atlas/Breakthrough_Listen_Observations_of_3I_Atlas_with_the_GBT.pdf.

3I/ATLAS: A Unified Framework and Live Test for Field Mediated ISO Dynamics

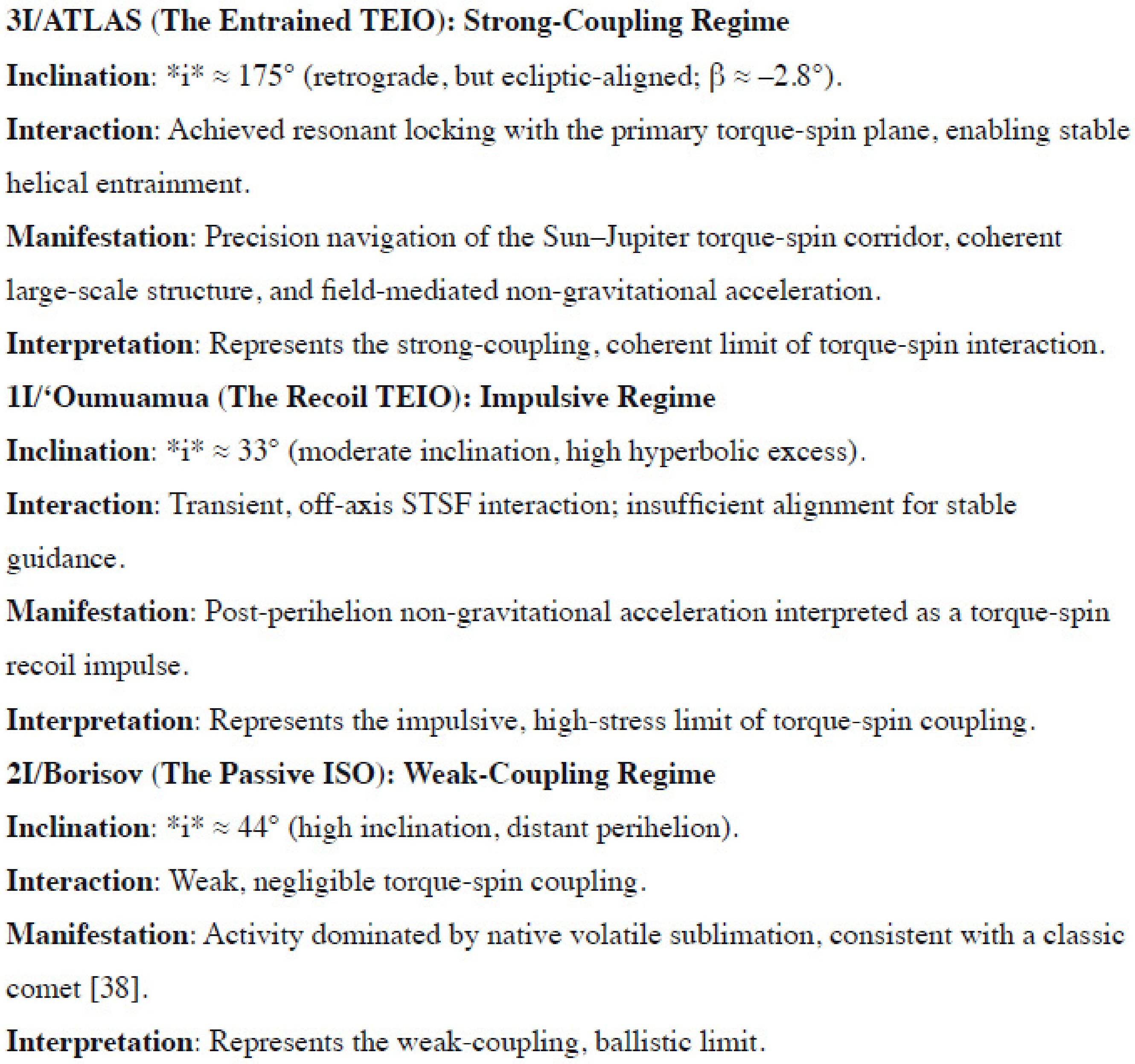
J Sarvon (Independent researcher)

In December 2025, J Sarvon released the following paper https://zenodo.org/records/18058232, which presents a time sensitive, phenomenological analysis of the interstellar object 3I/ATLAS, based exclusively on publicly reported observational data. The paper first enumerates a comprehensive set of observational constraints and evaluates the extent to which existing cometary, sublimation driven, and random trajectory interpretations account for them simultaneously. A minimal field mediated framework (TEIO) is then introduced at a descriptive level to illustrate how co-ordinated, testable predictions arise without fine tuned material assumptions. The interstellar object 3I/ATLAS confronts standard cometary models with a fundamental contradiction: its surface chemistry indicates billion-year Galactic Cosmic Ray processing, while its global dynamics exhibit large-scale coherence. A CO_2/H_2O ratio of 7.6 ± 0.3 points to a heavily irradiated, fragile crust, yet the object displays a spherical X-ray halo, persistent sunward jets, non-gravitational acceleration guiding it precisely toward Jupiter and an intact nucleus. This tension between long-term chemical processing and short-term dynamical integrity challenges models that treat irradiation solely as a source of structural weakness and passive degradation. The Torque-Intrained Interstellar Object (TEIO) model is introduced, in which 3I/ATLAS couples to a Solar Torque-Spin Field (STSF) — a heliospheric field structure generated by the Sun's rotation. The model further proposes that orbital inclination relative to the solar system's invariable plane governs the strength of torque-spin coupling, offering a unified explanation for the distinct behaviours of all three 1I/'Oumuamua, 2I/Borisov, and 3I/ATLAS.

[1] S Z Sheikh, et al 2025 https://arxiv.org/abs/2512.18142 (see page 12).

[2] D J Pisano et al (2025) *The Astronomer's Telegram*, 17499, 1

The three recognized interstellar objects (ISOs)—1I/‘Oumuamua, 2I/Borisov, and 3I/ATLAS exhibit a striking spectrum of dynamical and physical behaviours. The TEIO framework posits that this diversity is not random but follows a predictable continuum governed by a single geometric parameter: orbital inclination relative to the solar system’s invariable plane (where alignment is measured by min(*i*, 180° – *i*) for retrograde objects). Inclination dictates the efficiency of coupling with the structured Solar Torque-Spin Field (STSF), producing three distinct phenomenological classes, as shown in the graphic below.
Credit (graphic and caption): J Sarvon



3I/ATLAS (The Entrained TEIO): Strong-Coupling Regime

Inclination: *i* ≈ 175° (retrograde, but ecliptic-aligned; $\beta \approx -2.8°$).

Interaction: Achieved resonant locking with the primary torque-spin plane, enabling stable helical entrainment.

Manifestation: Precision navigation of the Sun–Jupiter torque-spin corridor, coherent large-scale structure, and field-mediated non-gravitational acceleration.

Interpretation: Represents the strong-coupling, coherent limit of torque-spin interaction.

1I/‘Oumuamua (The Recoil TEIO): Impulsive Regime

Inclination: *i* ≈ 33° (moderate inclination, high hyperbolic excess).

Interaction: Transient, off-axis STSF interaction; insufficient alignment for stable guidance.

Manifestation: Post-perihelion non-gravitational acceleration interpreted as a torque-spin recoil impulse.

Interpretation: Represents the impulsive, high-stress limit of torque-spin coupling.

2I/Borisov (The Passive ISO): Weak-Coupling Regime

Inclination: *i* ≈ 44° (high inclination, distant perihelion).

Interaction: Weak, negligible torque-spin coupling.

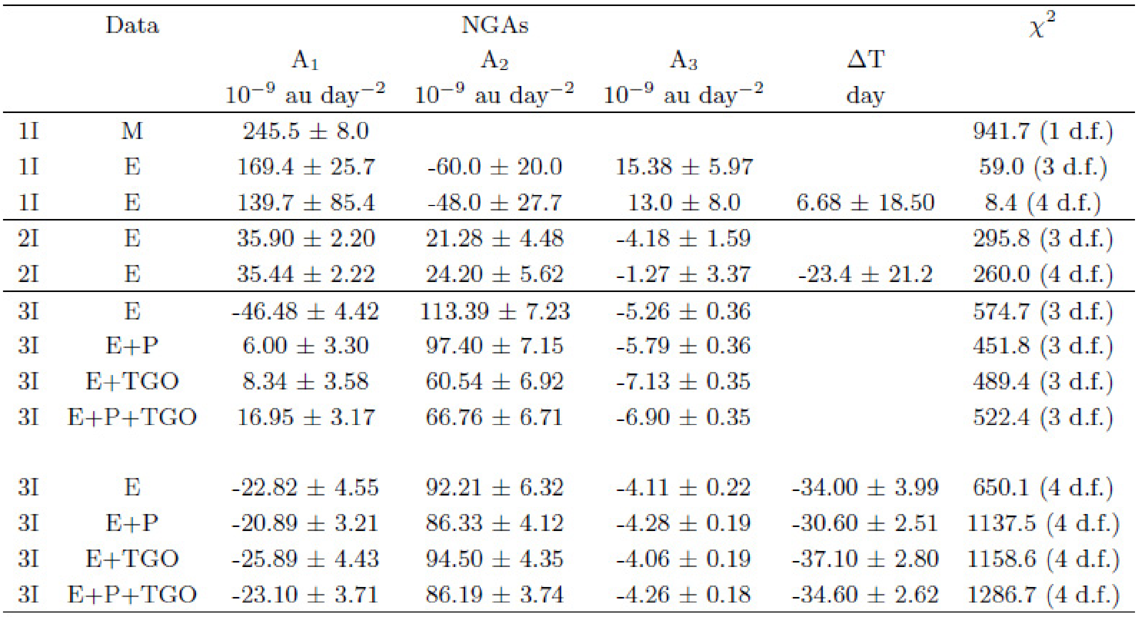
Manifestation: Activity dominated by native volatile sublimation, consistent with a classic comet [38].

Interpretation: Represents the weak-coupling, ballistic limit.

Determination of the Non-Gravitational Accelerations of the Interstellar Object 3I/ATLAS

T Marshall Eubanks (Space Initiatives Inc, USA) et al

In *Astrometry with Interplanetary Spacecraft: Determination of the Non-Gravitational Accelerations of the Interstellar Object 3I/ATLAS*, the authors report on the results of adding six observations from two interplanetary spacecraft to the orbit determination of 3I/ATLAS. These observations, from vantage points and times impossible with terrestrial instruments, reduce the non-gravitational acceleration parameters formal errors by 20% to 40% compared to solutions using just the terrestrial data available from May to December 2025. Using these data they find significant non-gravitational accelerations (NGAs) in the 3I/ATLAS trajectory, with a vector magnitude scaled to 1 AU of $(89.3 \pm 4.6) \times 10^{-9}$ AU day^{-2} and a time offset (ΔT) of -34.60 ± 2.62 days (ie an acceleration peaking ~one month before perihelion). This leads to a rough mass estimate for 3I/ATLAS of 44 million tons in early August 2025, equivalent to a CO_2 dominated nucleus radius $r_n \lesssim$ 374 m. See the paper here: https://www.researchgate.net/publication/398558191_Astrometry_with_Interplanetary_Spacecraft_Determination_of_the_Non-gravitational_Accelerations_of_the_Interstellar_Object_3IATLAS.



	Data	NGAs				χ^2
		A_1	A_2	A_3	ΔT	
		10^{-9} au day^{-2}	10^{-9} au day^{-2}	10^{-9} au day^{-2}	day	
1I	M	245.5 ± 8.0				941.7 (1 d.f.)
1I	E	169.4 ± 25.7	-60.0 ± 20.0	15.38 ± 5.97		59.0 (3 d.f.)
1I	E	139.7 ± 85.4	-48.0 ± 27.7	13.0 ± 8.0	6.68 ± 18.50	8.4 (4 d.f.)
2I	E	35.90 ± 2.20	21.28 ± 4.48	-4.18 ± 1.59		295.8 (3 d.f.)
2I	E	35.44 ± 2.22	24.20 ± 5.62	-1.27 ± 3.37	-23.4 ± 21.2	260.0 (4 d.f.)
3I	E	-46.48 ± 4.42	113.39 ± 7.23	-5.26 ± 0.36		574.7 (3 d.f.)
3I	E+P	6.00 ± 3.30	97.40 ± 7.15	-5.79 ± 0.36		451.8 (3 d.f.)
3I	E+TGO	8.34 ± 3.58	60.54 ± 6.92	-7.13 ± 0.35		489.4 (3 d.f.)
3I	E+P+TGO	16.95 ± 3.17	66.76 ± 6.71	-6.90 ± 0.35		522.4 (3 d.f.)
3I	E	-22.82 ± 4.55	92.21 ± 6.32	-4.11 ± 0.22	-34.00 ± 3.99	650.1 (4 d.f.)
3I	E+P	-20.89 ± 3.21	86.33 ± 4.12	-4.28 ± 0.19	-30.60 ± 2.51	1137.5 (4 d.f.)
3I	E+TGO	-25.89 ± 4.43	94.50 ± 4.35	-4.06 ± 0.19	-37.10 ± 2.80	1158.6 (4 d.f.)
3I	E+P+TGO	-23.10 ± 3.71	86.19 ± 3.74	-4.26 ± 0.18	-34.60 ± 2.62	1286.7 (4 d.f.)

NGAs The 1I/'Oumuamua M solution is from M Micheli et al 2018 [1], while solutions here used 111 of 113 observations from 18 Oct 2017 to 2 Jan 2018 with root mean square (rms) residuals of 0.11". The 2I/Borisov solution used 2117 of 2788 observations from 17 Mar 2019 to 28 Apr 2020 with rms residuals of 0.11", and the full 3I/ATLAS solution used 4194 of 4836 observations from 8 May to 1 Dec 2025 with an rms residual 1.49". The E data set includes all ground based optical data plus astrometry from the TESS and HST satellites, P represents the E data plus 2 Psyche points, on 8 Sep and 29 Oct and TGO the E data plus 4 Trace Gas Orbiter data points on 3 Oct; the errors assigned to these spacecraft measurements are 20", 0.25", 2" and 4", respectively.
Credit (graphic and caption): Eubanks et al, Table 1

[1] M Micheli, D Farnocchia, K J Meech, et al 2018, *Nature*, 559, 223, doi: 10.1038/s41586-018-0254-4

The size of 3I/ATLAS from non-gravitational acceleration

John C Forbes, Harvey Butler (University of Canterbury, New Zealand)

The third macroscopic interstellar object detected in the solar system recently passed through perihelion, with the best-fitting models of its trajectory now featuring non-gravitational accelerations. See the paper here https://arxiv.org/abs/2512.18341. the authors assess how much mass loss is required to produce plausible non-gravitational acceleration solutions and compare with estimates of the mass loss. They find that they are consistent when the nucleus of 3I/ATLAS is around 1 km in diameter. For a recent solution with a time lag in the acceleration from Eubanks et al [1], they find diameters between 820 metres and 1050 metres, assuming an outgassing asymmetry factor $\zeta = 0.5$ and a density of the comet nucleus $\rho = 0.5$ g cm^{-3}. The limits on the diameter scale as $(\zeta/\rho)^{1/3}$. Substantial extrapolation is required in general to compare non-gravitational accelerations to mass loss rates, so reliable estimates of the mass loss rate at other stages of the comet's trajectory will substantially reduce the systematic uncertainty in this estimate.

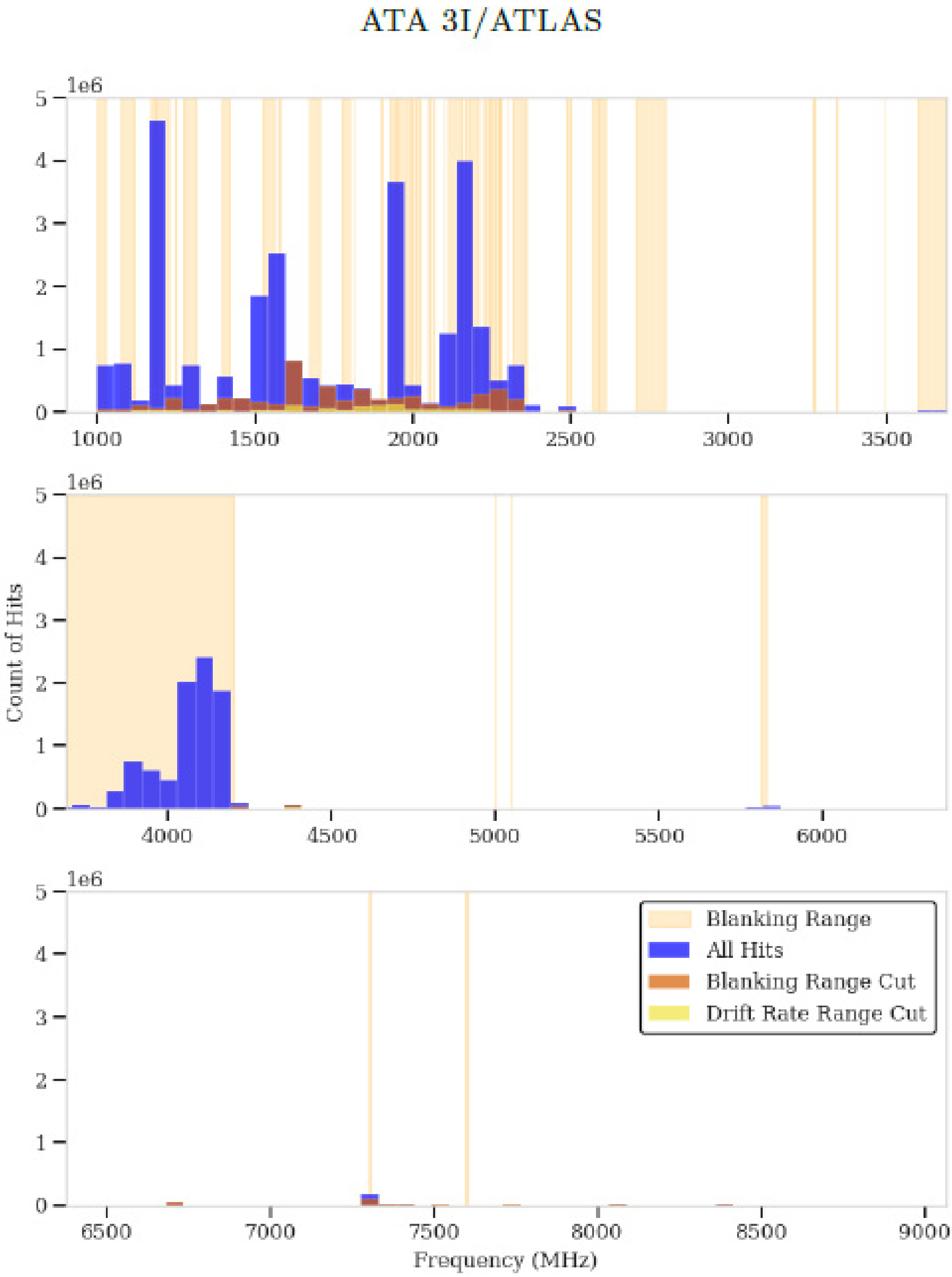
A Search for Radio Technosignatures from Interstellar Object 3I/ATLAS

Sofia Sheikh (SETI Institute, USA and Berkeley SETI Research Center, USA) et al

The authors used the SETI Institute's Allen Telescope Array to observe 3I/ATLAS from 1–9 GHz. In this campaign, they detected nearly 74 million narrowband hits in 7.25 hr of data using the newly-developed search pipeline bliss [2]. They then applied blanking in frequency and drift rate to mitigate Radio Frequency Interference (RFI) in their dataset, narrowing the dataset down to ~2 million hits. These hits were further filtered by the localization code NBeamAnalysis [3], and the remaining 211 hits were visually inspected in the time-frequency domain. They did not find any signals worthy of additional follow-up. Accounting for the Doppler drift correction and given the non-detection, they are able to set an Effective Isotropic Radiated Power (EIRP) upper limit of 10 - 110 W on radio technosignatures from 3I/ATLAS across the frequency and drift rate ranges covered by the survey. View the full paper here: https://arxiv.org/abs/2512.18142.

[1] T M Eubanks, A Hibberd, B G Bills, et al 2025, *Research Notes of the American Astronomical Society*, 9, 329, doi: 10.3847/2515-5172/ae2915
[2] https://github.com/UCBerkeleySETI/bliss
[3] https://github.com/isabelgerrard/NBeamAnalysis

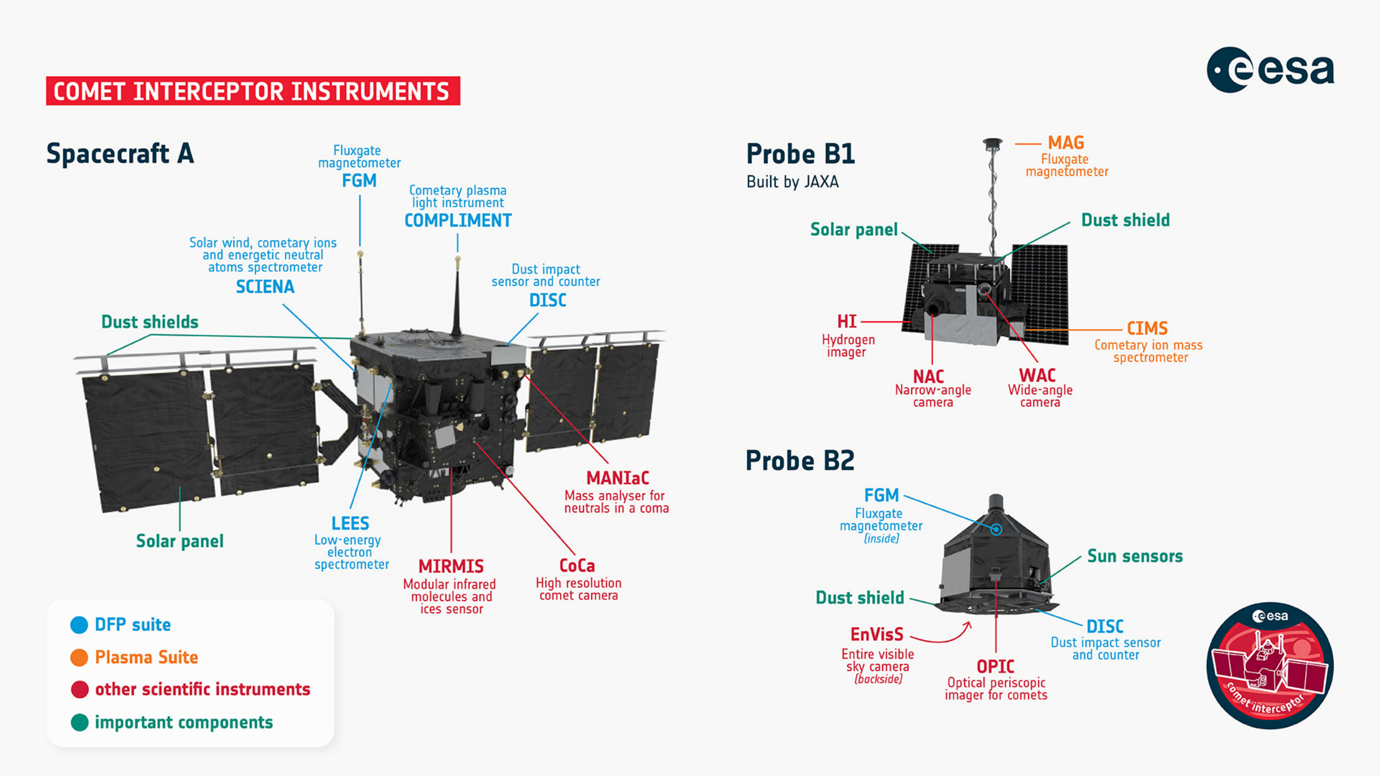
Frequency distribution of the ~74 million hits obtained in this survey. The top, middle, and bottom panels correspond to the "low" (1,000–3,688 MHz), "mid" (3688–6376 MHz), and "high" 6376–9064 MHz) frequency ranges, respectively. All y-axes are scaled to the same limits. Hits are shown in blue, blanking ranges are shown with yellow bars, the hits after blanking within the ranges are shown in brown, and the hits after limiting the drift rate range are shown in gold. Applying blanking ranges and drift rate limits significantly reduced dense clusters of hits (reducing the total number of hits by 97.4%) which improved their ability to process the data and detect putative signals associated with 3I/ATLAS.
Credit (graphic and caption): Sheikh et al, Figure 2



Intercepting Interstellar Objects

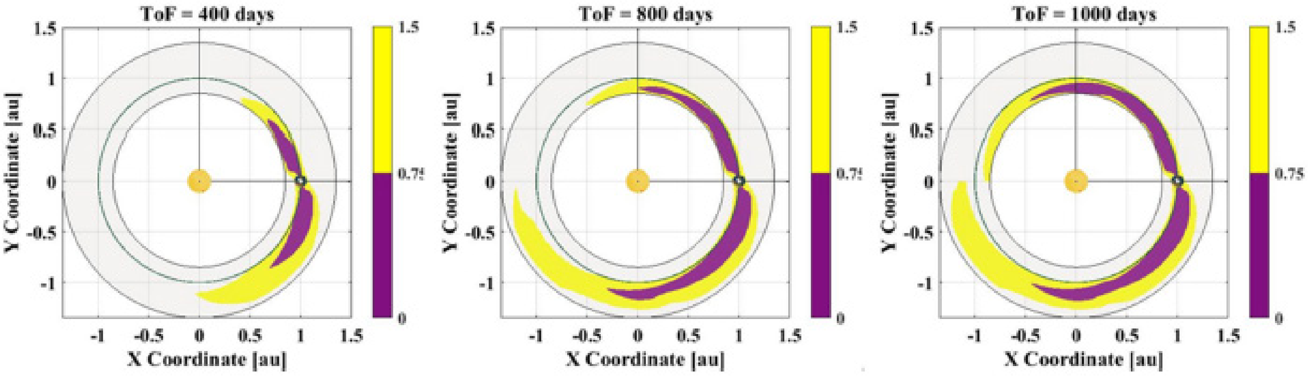
Colin Snodgrass (University of Edinburgh, UK) et al

A recent paper (https://arxiv.org/abs/2512.00492) describes how the ESA Comet Interceptor mission, which is due to launch in 2028/29 to a yet-to-be-discovered target, can provide a conceptual basis for a future mission to visit an Interstellar Object. Comet Interceptor will wait in space until a suitable long period comet is discovered, allowing rapid response to perform a fast flyby of an object that will be in the inner Solar System for only a few years; an enhanced version of this concept could realistically provide the first in situ investigation of a visitor from another star system.



Above
Comet Interceptor spacecraft and instruments (ESA).
Credit (graphic and caption): Snodgrass, Figure 1

Below
Accessible regions for CI comet encounters, relative to Earth, for different Δv (0.75 or 1.5 km/s) and time of flight (ToF) trajectories [1]
Credit (graphic and caption): Snodgrass, Figure 2



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[1] From J P Sanchez, D Morante, P Hermosin, et al 2021, *Acta Astronautica*, 188, 265, doi: 10.1016/j.actaastro.2021.07.014