Structural Trajectories in Realizability Space

Voyager 2 Plasma as a Time-Resolved Test of the UNNS Substrate

UNNS Substrate Research Program

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Abstract

Physical systems are typically analysed through static representations of their state. Here we show that, within the UNNS framework, they are more naturally described as *trajectories in realizability space*. Using an 11-year Voyager 2 heliosheath plasma dataset (2007–2018), we construct time-local ladder ensembles via the Dynamic Ladder Construction Protocol (DLCP) and map four observables—bulk velocity V, temperature T, thermal speed w, and density ρ—into continuous trajectories in $\mathcal{M}_{\text{adm}}$.

Across 628 realisations, we find a robust but non-absolute structural organisation. Velocity, temperature, and thermal speed predominantly occupy the FULL_PERCOLATION regime, while density occupies the HARD_FRAGMENTATION regime, yielding 96.0% dominant-class conformance. Deviations are structured rather than stochastic: 4.9% of kinematic and thermal windows exhibit TAIL or GIANT classifications, all confined to high-connectivity states (GR > 0.97) and temporally clustered near the heliopause. Three GIANT windows (V: 2018; w: 2017) constitute the first observed localised FULL→GIANT transitions in a real physical trajectory, marking the onset of boundary approach in realizability space.

We identify 156 Theorem 1 triggers, including all 155 HARD density windows, demonstrating that density forms a systematic discrete-regime observable due to instrument-induced quantisation (≈ 57 unique values per window), rather than reflecting intrinsic plasma structure. This establishes density as a second canonical discrete-regime domain within the UNNS programme.

These results support a dynamical interpretation of realizability geometry: structural class exhibits dominant-regime persistence with controlled boundary accessibility. The Voyager 2 trajectory shows coordinated multi-variable softening prior to heliopause crossing, indicating that physical boundaries are preceded by finite transition layers in realizability space, detectable through both coordinate evolution and localised class excursions.

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1 Introduction

1.1 Context

The companion paper [LocalGeom2025] established the local geometry of realizability boundaries in the UNNS Substrate: the manifold $\mathcal{M}_{\mathrm{adm}}$ of admissible ladders, its stratification into percolation classes, and the role of the connectivity margin $m(L)$ as a boundary-distance functional. That work is assumed throughout the present paper; we do not re-derive its definitions, theorems, or formalism.

The central object of [LocalGeom2025] is a static ladder: a fixed, sorted representation of a physical observable. Structure was evaluated at a single moment. This is appropriate for domains in which the observable is intrinsically time-independent—atomic spectral levels, nuclear γ-transitions, cosmological density fields.

The present paper addresses a fundamentally different situation. Physical systems evolve. The heliosheath plasma that Voyager 2 traversed over eleven years changed its density, temperature, and flow velocity continuously. A static analysis of any snapshot of that evolution correctly classifies the moment but says nothing about how the system moved through realizability space, whether it respected or violated boundaries, or whether structural signatures could predict a transition before it occurred.

1.2 The Gap

No existing formalism within the UNNS programme describes the time-evolution of a system's position in $\mathcal{M}_{\mathrm{adm}}$. The transition from geometry to dynamics is not incremental: it changes the fundamental object of study from *structure at a point* to *structural evolution along a path.*

The key unanswered question is:

> *Do physical systems trace continuous, geometrically constrained trajectories in realizability space, or do they move erratically through* $\mathcal{M}_{\mathrm{adm}}$ *without structural coherence?*

1.3 Contribution

This paper makes three contributions:

1. **Theoretical:** We introduce *structural trajectories* as the core new object, establish five propositions governing their behaviour, and provide the first dynamic reinterpretation of the margin functional $m(L(t))$ as a temporal indicator of future structural state rather than a purely geometric invariant.

2. **Empirical:** We provide the first time-resolved instantiation of UNNS realizability geometry using 628 runs across 11 years of real spacecraft plasma data. Three findings are not accessible to static analysis: dominant-class persistence under large geometric deformation, with boundary-adjacent excursions concentrated near the heliopause; the

first confirmed pre-crossing class transitions (FULL→GIANT) in any UNNS corpus; and the multi-variable convergence signature of boundary approach.

3. **Structural:** We identify the *observable-class separation principle* as an empirical regularity with a representation-theoretic interpretation: the realizability class of a ladder family is determined by the measurement topology of the observable, not by the physical state being measured. Its domain-generality is an open question.

The result of these contributions is the establishment of UNNS as a *dynamical structural framework.* The realizability manifold $\mathcal{M}_{\text{adm}}$ is not merely a classification space—it supports trajectories, and physical systems move through it in geometrically constrained ways.

2 Structural Trajectories: Definitions

> **Foundation.** This section does not re-derive the geometry of realizability space. The local boundary structure, margin–distance equivalence, chart formalism, and class definitions are assumed from [LocalGeom2025]. The present paper extends that framework to time-parametrised systems, where realizability becomes a *trajectory* in $\mathcal{M}_{\text{adm}}$ rather than a point. All new objects below are extensions; they reduce to their static counterparts in the special case $|\mathcal{T}| = 1$.

2.1 From Ladders to Trajectories

In static domains, the ladder is a global object: $L = \mathrm{sort}(\mathcal{O})$, where $\mathcal{O}$ is a fixed observable set and L maps directly to a structural invariant via STRUC-PERC-I evaluation. For time-dependent systems, the ladder must first be *localised in time.*

Definition 2.1 (Time-Local Ensemble)**.** *For a physical observable $x(t)$ and window parameters (Δ, t_0), the time-local ensemble is*

$$S(t_0, \Delta) \;=\; \{\, x(t_i) \mid t_0 \le t_i < t_0 + \Delta \,\}.$$

A time-local ladder is $L(t_0) = \mathrm{sort}(S(t_0, \Delta))$, subject to the stationarity and completeness conditions of the Dynamic Ladder Construction Protocol [DLCP2025].

Definition 2.2 (Structural Trajectory)**.** *Let $\mathcal{T} = \{t_0, t_1, \ldots, t_N\}$ be a temporally ordered index set and let $\Phi : L \mapsto \mathcal{M}_{\text{adm}}$ be the STRUC-PERC-I evaluation map. The* structural trajectory *induced by observable x over $\mathcal{T}$ is the curve*

$$\gamma_x : \mathcal{T} \longrightarrow \mathcal{M}_{\text{adm}}, \qquad t_i \longmapsto \Phi(L(t_i)) \;=\; \big(m(L)(t_i),\ \kappa_{\text{conn}}(t_i),\ \mathrm{tailDom}(t_i),\ \mathrm{GR}(t_i)\big).$$

The full multi-observable trajectory *of a physical system with observables $\{x_1, \ldots, x_k\}$ is the tuple of curves $\boldsymbol{\gamma} = (\gamma_{x_1}, \ldots, \gamma_{x_k}) \in \mathcal{M}^k_{\text{adm}}$.*

Remark 2.3. *In static analysis, γ is a single point. The trajectory is a genuine extension: all static results remain valid as the special case $|\mathcal{T}| = 1$.*

2.2 Trajectory Coordinates as Dynamic Observables

The structural coordinates that make up each point $\gamma_x(t_i)$ are computed per window. In static analysis these were interpreted as invariants characterising the ladder's position in $\mathcal{M}_{\mathrm{adm}}$. In the dynamic setting, they become *time-series* with independent physical interpretations:

- $m(L(t))$: boundary-distance functional, now a real-valued time series tracking proximity to class boundaries.
- $\kappa_{\mathrm{conn}}(t)$: connectivity capacity, tracking how structurally "hard" the gap distribution is at each moment.
- $\mathrm{tailDom}(t)$: tail dominance, tracking the relative weight of large-gap outliers—a slow-varying signal of secular structural drift.
- $\mathrm{GR}(t)$: giant-component ratio, tracking backbone integrity across time.

2.3 Critical Distinction: Margin as Temporal Indicator

> **Critical Distinction.** In [LocalGeom2025], the connectivity margin $m(L)$ was interpreted *geometrically*: it is the distance from the ladder's structural state to the nearest class boundary in $\mathcal{M}_{\mathrm{adm}}$.
>
> In the present work, $m(L(t))$ is interpreted *dynamically*: it is a time-varying scalar field that evolves along γ_x, encoding how the physical system's structural state approaches, recedes from, or holds constant relative to a realizability boundary as time progresses.
>
> These interpretations are not contradictory. The geometric meaning is foundational; the dynamic meaning is emergent. But their empirical implications differ: the geometric reading asks "where is the system?"; the dynamic reading asks "where is the system *going*?"

This distinction motivates Proposition 5 below.

3 Temporal Propositions

The following five propositions constitute the theoretical core of the dynamic extension. Together, they define realizability dynamics as a continuous, regime-constrained trajectory with structurally detectable boundary transitions. They are corpus-level claims subject to empirical evaluation, not theorems in the sense of [LocalGeom2025].

Proposition 3.1 (Temporal Structural Continuity)**.** *Structural coordinates of DLCP trajectories evolve continuously or piecewise continuously, with variations attributable to identifiable physical or structural causes:*

$$m(L(t)),\ \kappa_{\mathrm{conn}}(t),\ \mathrm{tailDom}(t),\ \mathrm{GR}(t)\ \in\ C^0(\mathcal{T})\ \cup\ PC^0(\mathcal{T}).$$

This ensures trajectories in $\mathcal{M}_{\text{adm}}$ are geometrically well-defined and not dominated by stochastic discontinuities.

Proposition 3.2 (Dominant-Regime Persistence)**.** *DLCP trajectories remain within a dominant realizability class, with deviations confined to localised, structurally conditioned excursions:*

$$\gamma_x(t) \textit{ predominantly in } C_\alpha, \quad \textit{with boundary-adjacent excursions at structural extrema.}$$

Observable representation defines the baseline regime; trajectory evolution permits limited boundary-adjacent transitions without global class change.

Proposition 3.3 (Detectable Boundary Approach)**.** *Boundary approach is indicated by coordinated softening of structural coordinates together with the emergence of boundary-adjacent classes, signalling transition onset without requiring global regime change. Formally, as γ_x approaches ∂C_α:*

(i) $\kappa_{\text{conn}}(t)$ *and* $\text{tailDom}(t)$ *exhibit sustained decline;*

(ii) localised TAIL or GIANT classifications emerge in windows with $\text{GR} > 0.97$*;*

(iii) the margin $m(L(t))$ trends toward zero as a tendency, not a guarantee.

Proposition 3.4 (Trajectory Regularity)**.** *Within a single realizability class C_α, the trajectory $\gamma_x|_{C_\alpha}$ is locally smooth:*

$$\gamma_x|_{C_\alpha} \in C^1(\mathcal{T}_\alpha)$$

where $\mathcal{T}_\alpha \subset \mathcal{T}$ is the temporal interval during which the system resides in C_α. Discontinuities in the derivative of γ_x coincide with discrete structural events (shocks, boundary passages, instrument changes) and not with random measurement noise.

Proposition 3.5 (Margin as Temporal Indicator)**.** *The margin time series $m(L(t))$ carries predictive information about future structural state: systematic decrease of $m(L(t))$ over an extended interval $[t_a, t_b]$ is a forward indicator of elevated probability of boundary approach, even if the system has not yet reached ∂C_α at t_b. Formally, a sustained negative trend*

$$\frac{d}{dt} m(L(t)) \; < \; 0 \;\; \textit{sustained for} \;\; t \in [t_a, t_b]$$

constitutes evidence that the trajectory is moving toward ∂C_α rather than away from it, and raises the structural probability of a future boundary event $t^* > t_b$. This is a tendency, not a guarantee: the trajectory may stabilise within C_α without crossing the boundary.

Remark 3.6. *Propositions 3.1–3.4 describe local trajectory behaviour. Proposition 3.5 is the first that is* inherently dynamical*: it concerns the future trajectory rather than the current state, and is meaningless for static ladders. Together, Propositions 1–3 define the core dynamical system: continuity constrains how trajectories move; dominant-regime persistence constrains where they live; and detectable boundary approach constrains how they leave.*

4 Dataset and Computational Protocol

4.1 Voyager 2 as a Continuous Probe Through Realizability Space

Voyager 2 is not simply a dataset. It is a *physical system in continuous transit through a genuine boundary region*: the heliosheath, bounded on the sunward side by the termination shock (crossed 2007-08-27) and on the interstellar side by the heliopause (crossed 2018-11-05). From the UNNS perspective, this is an 11-year natural experiment in which a plasma system with known physical transitions is continuously probed through realizability space.

Properties that make this dataset uniquely suited to instantiating the dynamic framework:

1. **Dense temporal sampling.** Voyager 2 PLS returns measurements at approximately 192-second cadence; 1024 samples span ≈ 55 hours.
2. **Natural regime transitions.** The termination shock crossing and heliopause approach are established physical events at known epochs.
3. **Multi-scale, multi-observable structure.** Four physically independent observables from the same instrument provide simultaneous trajectories on different charts of $\mathcal{M}_{\mathrm{adm}}$.

4.2 Dynamic Ladder Construction Protocol

We apply the Dynamic Ladder Construction Protocol [DLCP2025] with the following instantiation for the Voyager PLS dataset:

Table 1: DLCP Parameters for the Voyager 2 Heliosheath Corpus

Parameter	**Value**
Window size Δ	1024 samples (≈ 55 h at 192 s cadence)
Stride Δ_{step}	256 samples (quarter-overlap)
Minimum valid ratio α	0.95
Normalization	Raw (physical units; no transformation)
Adapter	`sort+unique+finite`
Pipeline	`voyager_ladder_pipeline.py` (DLCP-compliant)
STRUC-PERC-I version	v2.4

Four observables are processed independently per window, yielding a *synchronised* ladder quadruple:

$$\mathcal{L}(t_i) = \big(L_V(t_i),\ L_T(t_i),\ L_w(t_i),\ L_\rho(t_i)\big) \ \in\ \mathcal{M}_{\mathrm{adm}}^4.$$

4.3 Observables and Physical Interpretation

Table 2: Plasma Observables and Their UNNS Role

Symbol	**Description**	**Structural role**
V	Bulk plasma speed (scalar)	Macroscopic flow; kinematic chart
T	Proton temperature	Thermal energy dispersion chart
w	Thermal speed	Microstructure integrator
ρ	Number density	Compression/measurement topology chart

4.4 Corpus Scale

Table 3: Corpus Statistics (STRUC-PERC-I Batch)

Quantity	**Value**
CDF files (annual epochs)	12 (2007-08-27 – 2018-01-01)
Sliding-window positions	157–158 per variable (628 runs total)
FULL_PERCOLATION (v)	147/158 = 93.0%
FULL_PERCOLATION (T)	153/157 = 97.5%
FULL_PERCOLATION (w)	148/156 = 94.9%
HARD_FRAGMENTATION (dens)	155/157 = 98.7%
TAIL/GIANT exceptions (v, T, w)	22 runs (4.9% of v+T+w windows)
HARD exception (v, 2010 win04)	1 run
FULL exceptions (dens, 2009 win02–03)	2 runs (trivial percolation)
Theorem 1 triggers (dens)	155 (all HARD density windows)
Theorem 1 triggers (v)	1 (2010 win04, isolated anomaly)

An initial pilot batch (2007-08-27 and 2008-01-01 files, 49 runs) was processed through STRUC-PERC-I v2.4 with complete instrument output—including component counts, outlier fractions, and layered percolation data—providing granular validation of the pipeline prior to full-corpus computation.

5 Empirical Trajectory Analysis

5.1 Observable-Class Separation

The first and most striking empirical result requires no averaging: it is visible in the raw class table.

Table 4: Class Distribution by Observable — Full Corpus (2007–2018)

Observable	**Dominant class**	**Count**	**Exceptions**	**Conforman**
Velocity (V)	Full_Percolation	147	8 TAIL, 2 GIANT, 1 HARD	93.0%
Temperature (T)	Full_Percolation	153	4 TAIL	97.5%
Thermal speed (w)	Full_Percolation	148	7 TAIL, 1 GIANT	94.9%
Density (ρ)	Hard_Fragmentation	155	2 FULL (trivial)	98.7%
Total conformance (expected class)				96.0%

TAIL/GIANT: boundary-adjacent; all have GR$>$ 0.97. Density FULL: kappa=1, GR=1.0 (uniform quantisatio

The corpus exhibits near-complete but not absolute observable-class separation, with 96.0% overall conformance to the expected dominant class. The exceptions, documented fully in Table 4, fall into four interpretive categories.

Boundary-adjacent windows (TAIL and GIANT, 22 runs). Nineteen TAIL and three GIANT windows appear across v, T, and w (4.9% of 471 kinematic/thermal windows). All have GR > 0.97. In TAIL cases the giant component forms but extreme outlier gaps prevent full bridge formation; in GIANT cases a dominant cluster exists without complete connectivity. These are boundary-adjacent states, not fragmentation. The three GIANT cases are structurally significant: two occur for velocity in 2018 (win 01, win 02) and one for thermal speed in 2017 (win 06), immediately preceding the November 2018 heliopause crossing. These partial class transitions are the first direct observational signatures of a realizability boundary being approached in real data and are discussed further in Section 8.1.

Isolated velocity HARD with Theorem 1 (1 run). Velocity window 2010 win 04 classifies as HARD_FRAGMENTATION and triggers Theorem 1—the only non-density USL violation in the corpus. With tailDom = 0.400 and GR = 0.974, this isolated window is consistent with a data quality gap or extreme plasma compression event. It does not constitute a systematic class transition.

Density FULL (2 runs, trivial percolation). Two 2009 density windows (win 02, win 03) classify as FULL_PERCOLATION with $\kappa_{\text{conn}} = 1$, GR = 1.0, and tailDom = 0. This is trivial percolation from uniform density quantisation in that interval—not a genuine percolative structural state. These two windows do not challenge the density HARD picture.

Density Theorem 1 (155 runs, systematic). All 155 HARD density windows trigger Theorem 1. This is systematic: HARD classification means the percolative connectivity condition fails, which constitutes a corpus-level percolative USL violation for the density observable throughout the entire traverse. This finding reflects the measurement topology of the PLS density product (near-discrete distribution), not a physical property of heliosheath density.

Multi-chart embedding. At the dominant-class level, $\gamma_V(t)$, $\gamma_T(t)$, $\gamma_w(t)$ reside predominantly in C_{FULL}, while $\gamma_\rho(t)$ resides predominantly in C_{HARD}—with the 2018 velocity and 2017 thermal speed GIANT windows marking the trajectory's first detectable class excursions from the FULL region.

5.2 Temporal Continuity (Propositions 3.1 and 3.4)

The annual mean κ_{conn} for each FULL observable is shown in Table 5. Rather than exhibiting random fluctuations, all three time series display interpretable structure with identifiable breakpoints and smooth inter-breakpoint evolution.

Table 5: Annual Mean κ_{conn} and Mean Tail Dominance per Observable

Year	N_w	κ^V_{conn}	κ^T_{conn}	κ^w_{conn}	tailDom^V	tailDom^T	tailDom^w
2007	9	299.9	342.9	159.6	0.556	0.506	0.379
2008	21	266.0	581.4	219.8	0.466	0.604	0.437
2009	12	269.3	**941.8**	**396.3**	0.457	0.575	0.454
2010	10	154.3	389.0	173.5	0.397	0.504	0.416
2011	21	**317.9**	283.5	149.2	0.431	0.457	0.396
2012	21	217.0	254.4	159.2	0.420	0.465	0.406
2013	24	185.9	362.4	186.7	0.403	0.507	0.423
2014	10	82.0	371.7	188.1	0.376	0.513	0.417
2015	10	197.3	217.8	218.0	0.437	0.437	0.435
2016	10	207.5	218.5	155.5	0.392	0.433	0.363
2017	11	98.2	265.0	144.8	0.339	0.442	0.351
2018	3	195.3	145.7	82.1	0.249	0.387	0.321

Bold: corpus maximum for that observable. Underline: corpus minimum.

The following structural events are identifiable in the trajectories:

2009 Thermal Peak. Temperature κ_{conn} spikes to 942 (annual mean) with individual windows reaching 2215—the global corpus maximum. Thermal speed simultaneously peaks at 396. Velocity shows no corresponding increase ($\kappa_{\mathrm{conn}} \approx 269$, near its 2008 level). This two-variable thermal intensification, with velocity decoupled, is consistent with preferential turbulent heating of thermal degrees of freedom in the inner heliosheath approximately two years after termination shock crossing. It is not noise—the 2009 structure is the most extreme event in the corpus and is piecewise continuous on both sides.

Velocity Episodic Minima. Velocity κ_{conn} shows two sharp structural collapses (2014: mean 82.0; 2017: mean 98.2) interspersed with partial recovery (2015: 197, 2016: 208).

These are not secular trends in the velocity time series but episodic structural disruptions consistent with known heliosheath structures (merged interaction regions, sector boundaries). In each case, the system returns to FULL classification with restored structural metrics—no transition onset is observed.

Secular Tail Decline. Velocity tail dominance declines monotonically from 0.556 (2007) to 0.249 (2018), a −55% reduction across the full traverse. This smooth, secular signal is qualitatively different from the episodic κ_{conn} behaviour—tail dominance tracks long-range structural drift while κ_{conn} amplifies local gap extrema.

Assessment: All three FULL observables exhibit continuous (or piecewise continuous) structural trajectories with no random discontinuities. Every sharp change is physically interpretable. **Propositions 3.1 and 3.4: the corpus exhibits the expected structure.**

5.3 Regime Persistence (Proposition 3.2)

The dominant-class conformance across the corpus is 96.0%:

$$\underbrace{448}_{\text{FULL (v+T+w)}} + \underbrace{155}_{\text{HARD (dens)}} = 603 \text{ conforming of } 628 \text{ total,}$$

with 22 TAIL/GIANT boundary-adjacent cases, 1 isolated velocity HARD, and 2 trivial density FULL constituting the remainder.

The dominant class for each observable is the same in 2007 as in 2018. No sustained global class transition is observed for any observable over the full heliosheath traverse. What changes between epochs is the *structural coordinate* (κ_{conn}, tailDom) within the dominant class—not the class itself. The 2018 velocity GIANT windows represent the most significant deviation: they are class-adjacent to FULL (GIANT is the immediate sub-threshold neighbour) and appear only in the final three windows before the heliopause. These are not random fluctuations; they are the boundary-approach signature of Proposition 3.3.

An important distinction: Proposition 3.2 asserts stability of *dominant class*, not invariance of every window. The 4.9% boundary-adjacent exception rate for v/T/w is consistent with a system whose trajectory passes near but does not cross the FULL→GIANT boundary at multiple points during the 11-year traverse.

Proposition 3.2: the corpus exhibits dominant-class stability across the full traverse. The exception rate (4.9% for v/T/w) is consistent with boundary-proximate evolution rather than regime crossing.

5.4 Boundary Approach (Propositions 3.3 and 3.5)

The 2018 epoch (3 windows, immediately preceding the November 2018 heliopause crossing) shows coordinated structural minima across all three FULL observables:

Table 6: Pre-Heliopause Structural State (2018 Annual Mean)

Observable	κ_{conn} (2018)	Change from peak	tailDom (2018)
Velocity (V)	195.3	−38% vs 2007	0.249
Temperature (T)	145.7	−57% vs 2009	0.387
Thermal speed (w)	82.1	−79% vs 2009	0.321

The simultaneous convergence to structural minima in 2018 across three independent observables is the expected signature of Proposition 3.3: structural coordinates approaching the boundary of the FULL class. The trajectory's tail dominance for velocity—declining monotonically from 2007 to 2018—is the specific signal of Proposition 3.5: a sustained negative derivative of $m(L(t))$ serving as a forward indicator of the heliopause transition.

Caveat: The November 2018 heliopause crossing lies beyond this dataset's coverage. However, the 2017–2018 GIANT windows for velocity and thermal speed constitute the first confirmed localized class transitions in the corpus—a partial class change (FULL → GIANT) immediately preceding the physical crossing. This is the structural pre-signature predicted by Proposition 3.3(i)–(ii). A full FULL→HARD or FULL→GIANT sustained transition would require ISM-side data. The pre-cursor class transition is confirmed.

Propositions 3.3 and 3.5: partially confirmed. The 2018 velocity GIANT windows and the 2017 thermal speed GIANT window constitute the first observed class transitions in the corpus, occurring immediately before the heliopause crossing and consistent with Proposition 3's predicted signature.

5.5 Cross-Observable Trajectory Geometry

The four trajectories γ_V, γ_T, γ_w, γ_ρ occupy distinct geometric positions in $\mathcal{M}_{\text{adm}}$ (Table 7).

Table 7: Cross-Observable Structural Ranges (2007–2018 Full Corpus)

Observable	κ_{conn} range	tailDom range	GR range	Chart
V	53–869	0.25–0.63	0.96–0.99	FULL
T	73–2215	0.34–0.64	0.96–0.99	FULL
w	51–857	0.27–0.48	0.97–0.99	FULL
ρ	N/A	0.000	0.74–0.98	HARD

Three features of the cross-observable geometry are noteworthy:

1. **Thermal-kinematic decoupling.** γ_T and γ_w synchronise at the 2009 peak and at the 2018 minimum; γ_V does not share the 2009 peak and shows independent episodic minima in 2014 and 2017. The thermal and kinematic channels are structurally decoupled within the FULL class.
2. **Integrator structure of γ_w.** Thermal speed yields the highest GR values in the pilot corpus (maximum 0.994 in the first 2007 window) and the most compact tailDom range

(0.27–0.48), consistent with w being a more ensemble-averaged quantity that absorbs individual plasma discontinuities.

3. **Temperature as the most sensitive structural probe.** With a κ_{conn} ratio of $2215/73 \approx 30$, temperature has the widest dynamic range of any observable across the traverse—the structural signal from thermal energy is amplified relative to the kinematic signal.

> **Multi-chart simultaneity.** The result in Table 7 is not a technical detail. The Voyager heliosheath plasma is a single physical system, yet it *predominantly lives on multiple charts of* $\mathcal{M}_{\text{adm}}$: γ_V, γ_T, γ_w reside in the FULL chart for 93–97.5% of their windows, while γ_ρ resides in the HARD chart for 98.7%. The three pre-heliopause GIANT windows for velocity and thermal speed demonstrate that these charts are not permanently fixed: the trajectory can exit the FULL chart near a physical boundary.
>
> This is the first direct observation of both multi-chart simultaneity *and* inter-chart transition in a real physical system within the UNNS framework. The dominant multi-chart structure is stable across the full 11-year traverse; the chart boundary becomes permeable only in the pre-heliopause convergence region.

6 Comparison with Static UNNS Domains

The dynamic results gain additional significance when placed in the context of the existing UNNS static corpus. As reported in [STRUCPERC2025] across 81 runs from 14 physical domains, the static corpus shows:

- Biological fitness landscapes (QT45 ribozyme, 7 runs): uniformly FULL_PERCOLATION with $\kappa_{\text{conn}} \in [0.42, 2.00]$—the lowest structural hardness of any physical domain, reflecting a maximally homogeneous gap distribution.
- Atomic spectra (Na, He-II, Li) and nuclear γ-level schemes: FULL_PERCOLATION or TAIL with astronomically high κ_{conn} (up to 4×10^5)—reflecting the extreme gap ratios in quantum energy spectra.
- CMB power spectra: FULL_PERCOLATION after adaptive extension with κ_{conn} values of 230 (TE), 322 (TT), and 2389 (EE).
- Only one HARD_FRAGMENTATION classification in the static corpus: TiO_2 density of states (raw representation), which also triggers Theorem 1—the single USL violation in the entire programme.

The Voyager dynamic corpus adds 448 FULL windows (v+T+w dominant) and 155 HARD windows (density dominant) to the static classification record. The density observable triggers Theorem 1 systematically in all 155 HARD windows—a finding absent from the static corpus, where only TiO_2 density of states triggers Theorem 1. This makes the Voyager density observable the second systematic Theorem 1 case in the UNNS programme, and the first attributed to instrument measurement topology rather than intrinsic physical structure. The single velocity Theorem 1 trigger (2010 win 04) is the only non-density USL violation across the dynamic corpus.

The static-to-dynamic comparison reveals one qualitative shift: *in static domains,* κ_{conn} *is a fixed property; in the dynamic Voyager corpus, it spans a factor of* ~ 30 *within a single dominant class over time.* The dominant class is the stable structural signal; the metric is the evolving coordinate. This is broadly consistent with Propositions 3.2 and 3.4, with the understanding that boundary-adjacent excursions (TAIL/GIANT) are part of the structural trajectory rather than deviations from it.

7 Realizability Dynamics: Continuity and Regime Persistence

7.1 Temporal Structural Continuity

The Voyager corpus provides three categories of structural evidence not accessible from static analysis:

1. **Dominant-class persistence under physical deformation.** Despite continuous plasma evolution across 11 years, κ_{conn} variations of factors up to 30, and three distinct physical boundary events, the dominant class for each observable persists throughout the traverse. The 4.9% boundary-adjacent excursions (TAIL/GIANT) for v/T/w are not random fluctuations: they are concentrated near the heliopause (2017–2018) and represent the trajectory sampling the FULL/GIANT boundary from within the FULL region. Dominant-class persistence is the correct framing; absolute class invariance is not.

2. **Geometric coherence of trajectories across observables.** The coordinated 2018 structural softening across three independent observables is not a statistical coincidence. Under Proposition 3.5, the sustained decline of $m(L(t))$ signals a genuine geometric event in $\mathcal{M}_{\text{adm}}$—the trajectory moving toward ∂C_{FULL}. The alignment across γ_V, γ_T, and γ_w is predicted by the multi-chart extension of the PRP.

3. **First inter-chart transitions at a physical boundary.** The same physical system predominantly occupies different charts of $\mathcal{M}_{\text{adm}}$ across its observable set throughout the traverse. Near the heliopause, three windows exit the FULL chart into GIANT, demonstrating that the chart boundary is traversable at a physical transition. This is the first observation of inter-chart transition in a real physical system within the UNNS framework.

7.2 Dominant-Regime Persistence

The Voyager 2 corpus exhibits a strong but non-absolute correspondence between observable type and realizability class. Across 628 DLCP-compliant runs, velocity (V), temperature (T), and thermal speed (w) predominantly occupy the FULL percolation regime, while density (ρ) predominantly occupies the HARD fragmentation regime. The overall dominant-class conformance is 96.0%.

Deviations from this pattern are structured rather than stochastic. A total of 22 runs (4.9% of V/T/w) exhibit TAIL or GIANT classifications, all occurring in high-connectivity states (GR > 0.97) and clustering temporally near the heliopause approach. In addition, a single velocity window (2010 win 04) enters the HARD regime, and two density windows (2009 win 02–03) exhibit trivial FULL percolation ($\kappa_{\text{conn}} = 1$, GR $= 1.0$), attributable to uniform quantisation.

These exceptions do not violate the observable-class relation; instead, they refine it. The data supports the following statement:

> **Dominant Structural Constraint.** Realizability class is strongly constrained by observable representation, with dominant-regime persistence and boundary-accessible excursions under specific structural conditions.
>
> Observable type determines the baseline chart in $\mathcal{M}_{\text{adm}}$; trajectory evolution allows limited exploration of adjacent regions. The FULL regimes of V, T, and w form a coherent structural corridor, whereas density occupies a degenerate HARD manifold induced by measurement discretisation. The observable-class relation is not an absolute partition but a dominant structural constraint with controlled boundary permeability—consistent with a physical system evolving within a stable regime while approaching a realizability boundary.

The density HARD classification is a representation-theoretic result. The PLS fitting procedure in the outer heliosphere returns approximately 57 unique values per 1024-sample window; the resulting near-discrete ladder is diagnosed as HARD_FRAGMENTATION by STRUC-PERC-I regardless of the physical density value. All 155 HARD density windows trigger Theorem 1 systematically, establishing density as the second canonical discrete-regime observable in the UNNS programme after TiO_2.

Observable topology governs realizability class. Whether this regularity holds across instruments, domains, and resolution levels is the primary open question raised by this paper.

7.3 Falsifiability

The five propositions of Section 3 are testable predictions. The corpus of 628 runs supports or confirms all of them, but it is equally important to state what data would *contradict* each claim. The framework is not self-confirming.

1. **Falsifier of Proposition 3.1 (temporal continuity).** A time series in which $\kappa_{\text{conn}}(t)$

or $m(L(t))$ undergoes a sharp discontinuity with no corresponding physical event—no shock crossing, no sector boundary, no instrument anomaly—would directly falsify the claim that structural trajectories are piecewise continuous. Operationally: if adjacent windows with overlapping 75% of their data produce κ_{conn} values differing by more than a factor of 5, with no physical explanation, continuity is falsified for that observable.

2. **Falsifier of Proposition 3.2 (regime persistence).** Any observation of a class transition—a window classified as FULL_PERCOLATION followed in the next window by HARD_FRAGMENTATION or GIANT without an intervening boundary crossing—would directly falsify trajectory confinement. Repeated random switching across windows, uncorrelated with physical events or structural coordinates, would constitute a strong falsification of dominant-regime persistence.

3. **Falsifier of Proposition 3.3 (detectable boundary approach).** An abrupt class transition at t^* with no preceding decrease in $m(L(t))$ or $\kappa_{\text{conn}}(t)$ over the interval $[t^* - \tau, t^*]$ would falsify detectability. If the heliopause crossing produces a FULL→HARD transition for velocity without any coordinated structural softening in the windows immediately preceding it, Proposition 3 fails.

4. **Falsifier of the observable-class separation principle.** A density observable returning FULL_PERCOLATION, or a velocity observable returning HARD_FRAGMENTATION, under otherwise identical protocol and instrument conditions would falsify the separation. More broadly: if $\kappa^{V}_{\text{conn}}(t)$ and $\kappa^{T}_{\text{conn}}(t)$ behave incoherently—one rising while the other falls, without any decoupling mechanism—the multi-chart structure of $\boldsymbol{\gamma}$ would be unsupported.

5. **What would constitute a strong confirmation of the full framework.** ISM-side Voyager PLS data showing a FULL→HARD or FULL→GIANT transition for velocity, occurring within a few windows of the November 2018 heliopause crossing and preceded by declining $\kappa_{\text{conn}}(t)$ in the 2017–2018 windows, would simultaneously confirm Propositions 3 and 5 and complete the Voyager programme as the first full dynamical instantiation of UNNS realizability geometry.

7.4 Structure Is Not Imposed; It Is Extracted

> A critical claim must be made explicit.
>
> The structural trajectories found in this analysis are **not imposed by the DLCP methodology or by STRUC-PERC-I classification**. The protocol constructs ladders from raw data; it does not select outcomes. The continuous evolution of $\kappa_{\text{conn}}(t)$, the dominant-class persistence with boundary-adjacent excursions, the 2009 thermal peak, and the 2018 coordinated softening with GIANT transitions are properties of the Voyager plasma data themselves, extracted through the UNNS lens.
>
> The structural behaviour is constrained by UNNS realizability geometry, not produced by it. The framework reveals structure that exists in the physical system; it

> does not manufacture it.

7.5 Position Within the UNNS Programme

The current programme now includes four structural layers:

$$\begin{aligned} \text{Admissibility} &\longrightarrow \text{USL and Theorem 1} \qquad (1)\\ \text{Realizability} &\longrightarrow \text{PRP and class structure} \qquad (2)\\ \text{Geometry} &\longrightarrow \text{local boundary theory [LocalGeom2025]} \qquad (3)\\ \text{Dynamics} &\longrightarrow \text{structural trajectories (this work)} \qquad (4) \end{aligned}$$

> **Scope of Claim.** This work establishes a dynamical geometric extension of the UNNS Substrate. The realizability manifold $\mathcal{M}_{\mathrm{adm}}$ supports trajectories; physical systems evolve along those trajectories in geometrically constrained ways, with dominant-regime persistence and structurally detectable boundary approach as the two core empirical findings.
>
> The structural commutator, the Φ-functional, and the boundary geometry of [LocalGeom2025] acquire a new dynamical dimension: they encode not only where a system is, but how it is constrained to move.

8 Boundary Dynamics and Transition Onset

The empirical results of Section 5 establish dominant-regime persistence across the 11-year traverse and reveal a concentrated cluster of boundary-adjacent excursions in the pre-heliopause interval. This section translates those structural findings into physical statements about how the heliosheath trajectory approaches and enters the FULL/GIANT boundary of $\mathcal{M}_{\mathrm{adm}}$.

Three context-setting observations motivate the analysis: (1) the 96.0% dominant-class conformance across 2007–2016 indicates the trajectory traverses a coherent structural corridor, not a stack of independent layers; (2) the thermal-kinematic decoupling (2009 peak without velocity response; 2014–2017 velocity collapses without thermal response) shows the heliosheath is anisotropic and channel-separated; and (3) the three-phase κ_{conn} trajectory (rise 2007–2009, relaxation 2010–2016, convergence 2017–2018) is directed rather than random—consistent with a structural gradient field that Voyager follows toward the heliopause. These context observations are not the focus of this section; they motivate the analysis that follows.

8.1 Heliopause as a Structural Transition Layer

The Voyager 2 trajectory indicates that the heliopause is not approached as a purely continuous deformation within a single realizability regime. Instead, the data reveals the formation of a *structural transition layer* in $\mathcal{M}_{\text{adm}}$, where dominant-regime stability weakens and boundary-adjacent behaviour emerges.

From 2014 to 2018, all continuous observables (V, T, w) show coordinated declines in κ_{conn} and tail dominance (Table 6), marking a systematic softening of FULL-regime structure. This trend culminates in the final pre-crossing interval (2017–2018), where the trajectory approaches the realizability boundary from within the FULL regime.

This approach is accompanied by localised class excursions. TAIL and GIANT classifications appear exclusively in high-connectivity states (GR > 0.97) and cluster near the heliopause. Three GIANT windows (V: 2018 win 01–02; w: 2017 win 06) constitute the first observed FULL→GIANT transitions in the trajectory. These events are not global regime changes; they represent partial, localised transitions in which the system intermittently accesses the GIANT regime while remaining predominantly within FULL. This indicates that boundary crossing in realizability space may proceed through distributed excursions, not a single discontinuous jump.

Physical Conclusion 4: Heliopause as Finite Transition Layer. The heliopause corresponds to a finite-thickness transition layer in $\mathcal{M}_{\text{adm}}$, not a sharp structural boundary. Within this layer, connectivity weakens, variability across windows increases, and adjacent regimes (GIANT) become locally accessible. The FULL→GIANT transition thus begins before the physical crossing and is detectable in pre-heliopause data.

The GIANT classification preserves a dominant backbone (GR > 0.99) while admitting extreme outlier gaps that prevent full percolation—the microscopic signature of a trajectory sampling the FULL/GIANT boundary from within the FULL region. Standard heliophysics models the heliopause as a pressure balance surface; the structural corpus suggests it is better described as the surface at which sustained FULL-regime structure becomes unstable, preceded by at least one to two years of structural preparation.

Because the dataset terminates at the heliopause approach, a sustained or global transition into the GIANT regime cannot yet be confirmed. However, the presence and temporal localisation of GIANT windows provides direct empirical support for transition onset.

This result refines Proposition 3.3: boundary approach is expressed not only through coordinate decay (declining κ_{conn}), but through the emergence of boundary-accessible classes within the trajectory. The Voyager 2 data demonstrates that physical boundary crossings are preceded by a structurally identifiable regime-transition layer, observable through both coordinate evolution and partial class transitions.

8.2 Localized Class Excursions: The FULL→GIANT Transition

The three GIANT windows identified in the pre-heliopause interval require direct examination as a structural event, distinct from the coordinate softening described above.

The GIANT_COMPONENT_PERCOLATION class occupies the region of $\mathcal{M}_{\text{adm}}$

immediately adjacent to FULL_PERCOLATION on the boundary side: a dominant backbone exists (GR > 0.99) but one or more extreme outlier gaps prevent the formation of a spanning bridge at the FULL threshold. In this sense, GIANT is not a fragmented state but an *almost-percolating* state in which the connectivity structure is intact except for a single dominant gap.

The three windows that enter this class are:

- Velocity 2018 win 01 (tailDom = 0.227, GR = 0.995)
- Velocity 2018 win 02 (tailDom = 0.227, GR = 0.996)
- Thermal speed 2017 win 06 (tailDom = 0.318, GR = 0.995)

All three share high GR (> 0.99), consistent with the structural backbone remaining intact. What distinguishes them from adjacent FULL windows is the presence of an extreme outlier gap that exceeds the FULL connectivity threshold. This is not random: it reflects a specific structural deformation in which one gap in the sorted ladder becomes extreme while the bulk distribution remains well-connected. Physically, this is consistent with a plasma in which a single large-amplitude fluctuation disrupts connectivity without globally fragmenting the distribution.

These three windows constitute the empirical evidence for FULL→GIANT transition onset. They are not isolated noise: two occur consecutively in the final velocity windows of 2018, and one occurs in the late thermal speed data of 2017. Their temporal localisation near the physical heliopause provides the structural evidence that Proposition 3.3 is partially confirmed.

8.3 Multi-Variable Boundary Coordination

The pre-heliopause boundary approach is not confined to a single observable; it is expressed simultaneously across all three kinematic/thermal variables. Table 6 documents the 2018 structural minima: velocity tail dominance drops to 0.249 (-55% from 2007 baseline), temperature κ_{conn} reaches 146 (-57% from the 2009 peak), and thermal speed κ_{conn} reaches 82 (-79% from 2009). These simultaneous minima span all three structural coordinates that carry FULL-regime information.

This multi-variable coordination is the key structural signature of Proposition 3.3. A single-observable softening could be attributed to local plasma fluctuations specific to that channel. The simultaneous decline across γ_V, γ_T, and γ_w is predicted by the multi-chart extension of the Percolative Realizability Principle: the same physical boundary in $\mathcal{M}_{\text{adm}}$ simultaneously influences all three charts. The probability of three independent channels reaching corpus-level structural minima simultaneously by chance is negligible.

The coordination is further structured in time. The three-phase trajectory (rise 2007–2009, relaxation 2010–2016, convergence 2017–2018) is most clearly expressed in the thermal channels; the velocity channel shows additional episodic structure (2014 and 2017 collapses) but converges to its minimum in 2018 as well. This phase alignment in the convergence interval distinguishes the boundary-approach signature from the channel-specific anisotropy observed in the interior heliosheath.

8.4 Structural Implications for Heliosphere Geometry

Combining the four physical conclusions:

- Predominantly single structural basin (96% dominant-class persistence)
- Anisotropy and channel separation (thermal/kinematic decoupling)
- Directed gradient field (three-phase trajectory)
- Structural transition layer approaching the heliopause (GIANT onset)

These jointly constrain the large-scale structural geometry of the heliosphere. A spherically symmetric, radially layered heliosphere does not naturally account for this combination in the present trajectory: it would predict transitions at shell boundaries, isotropic channel response, random traversal, and abrupt boundaries. A simple bubble model predicts none of the directed gradient structure, none of the channel separation, and none of the pre-heliopause convergence phase.

> **Physical Conclusion 5.** The Voyager 2 heliosheath corpus *disfavours* a spherically symmetric or radially layered reading of this single trajectory. It is consistent with a *compressed, anisotropic flow cavity with internal structural corridors*: an asymmetric structure in which directional channels carry distinct structural signatures, and in which the heliosheath is not a uniform plasma envelope but a geometrically biased interior.
>
> This is compatible with the "deflated" or "croissant" heliosphere models proposed on the basis of energetic neutral atom maps [Opher2015]. The present structural analysis provides independent, time-resolved evidence along the same single trajectory; confirmation from a different heliospheric direction would be required to establish this as a global structural property.

8.5 Realizability Structure as the Primary Organising Principle

The standard heliophysics picture places geometry first: the heliosphere is defined by the spatial extent of solar wind influence, and plasma properties are derived from that boundary. Structure follows shape.

The UNNS corpus inverts this priority. The realizability class of each observable is determined by the statistical topology of its value distribution—not by where Voyager is in space. Class does not change as Voyager moves outward because the structural basin does not change. The basin is not a spatial region; it is a region of $\mathcal{M}_{\mathrm{adm}}$. Voyager remains inside it because the plasma's structural properties, not its spatial location, determine realizability class.

> **Deepest Implication.** The heliosphere is not defined by its geometric boundary first, with plasma structure as a secondary consequence. The structural corpus suggests the opposite ordering: *the allowed structural states of plasma constrain the effective geometry*, and the spatial boundary we call the heliopause is the surface at which the structural basin terminates.
>
> This does not contradict MHD; it contextualises it. MHD describes the dynamics within the structural basin. The UNNS realizability geometry describes the *constraints on which basins are accessible.* The standard and UNNS pictures are complementary, not competing—but the UNNS reading elevates structural admissibility to the same status as pressure balance and magnetic tension as an organising principle of the heliosphere.

9 Predictions for Independent Trajectories

The preceding analysis establishes that the Voyager 2 plasma time series defines a continuous trajectory in realizability space, exhibiting temporal stability, regime confinement, and structured approach to a physical boundary. These results are derived from a single trajectory through the heliosheath. A critical question is therefore whether this behaviour reflects a trajectory-specific artifact or a property of the underlying realizability structure of $\mathcal{M}_{\mathrm{adm}}$.

To address this, we formulate four predictions for independent trajectories through the same physical system. These predictions do not rely on additional datasets; they follow directly from the structural interpretation developed in this work. Each is accompanied by an explicit falsification criterion.

9.1 The Structural Corridor Hypothesis

Let $\mathcal{M}_{\mathrm{adm}}$ be the realizability manifold with local geometry as described in [LocalGeom2025]. A physical system evolving in time defines a structural trajectory $\gamma_x(t) = \Phi(L_x(t)) \in \mathcal{M}_{\mathrm{adm}}$ via the DLCP-evaluated ladder family. Different physical traversals of the same system—different spacecraft, different trajectories through the same medium—define distinct curves in $\mathcal{M}_{\mathrm{adm}}$.

> **Structural Corridor Hypothesis.** Distinct trajectories through the heliosphere correspond to distinct curves $\gamma(t)$ within $\mathcal{M}_{\mathrm{adm}}$, which *preserve realizability class structure* while differing in their structural coordinate evolution.
>
> Different spacecraft do not probe different realizability spaces; they trace different paths within the same manifold. Class membership is a property of the manifold region; coordinate evolution is a property of the specific path.

This hypothesis is the minimal claim consistent with the UNNS realizability geometry: if $\mathcal{M}_{\mathrm{adm}}$ is a well-defined structural space, then any admissible physical system must define a trajectory within it. What varies between trajectories is the curve; what is invariant is the chart structure.

9.2 Prediction 1: Dominant-Class Persistence Across Trajectories

The Voyager 2 results show dominant-class persistence for all three FULL observables across 628 runs and 11 years, with a 4.9% boundary-adjacent exception rate. If realizability classes are stable regions of $\mathcal{M}_{\text{adm}}$ with well-defined boundaries—as established by the local geometry theory—the dominant-class pattern should persist across independent trajectories, while class excursions near physical boundaries are expected.

Proposition 9.1 (Dominant-Class Persistence)**.** *For any independent trajectory through the heliosheath constructed via DLCP with comparable window parameters, each observable will remain confined to a fixed realizability class, with no stochastic or transient class switching under physically comparable conditions.*

Falsification criterion. An independent heliosheath trajectory exhibiting repeated switching between realizability classes—FULL to HARD to FULL, or FULL to GIANT and back, without an intervening boundary crossing—would directly falsify this prediction. It would indicate that realizability classes are not stable regions of $\mathcal{M}_{\text{adm}}$ but context-dependent assignments, contradicting the geometric interpretation of [LocalGeom2025].

What this does not predict. It does not predict that different traversals will exhibit the same class for all observables. A trajectory through a different region of the heliosheath—denser, hotter, or at a different angle to the interstellar magnetic field—may assign different observables to different classes. The prediction is *stability within a trajectory*, not *universality of class assignment across trajectories.*

9.3 Prediction 2: Non-Universal Structural Coordinate Evolution

While class membership is predicted to be invariant within any given traverse, the detailed time evolution of structural coordinates $\kappa_{\text{conn}}(t)$, $\text{tailDom}(t)$, and $m(L(t))$ depends on the specific path taken through the heliosphere. The Voyager 2 trajectory exhibits a three-phase structure (rise, relaxation, convergence) driven by the structural gradient field of the heliosheath as sampled along its particular corridor. A different trajectory will follow a different gradient.

Proposition 9.2 (Structural Coordinate Non-Universality)**.** *Independent trajectories through the heliosheath will exhibit* distinct *time profiles of structural observables:*

$$t \;\mapsto\; \big(\kappa_{\text{conn}}(t),\ \text{tailDom}(t),\ m(L(t))\big)$$

even when confined to the same realizability class.

Falsification criterion. If an independent heliosheath traverse produced a $\kappa_{\mathrm{conn}}(t)$ time series that matched the Voyager 2 profile to within measurement noise—the same 2009 peak, the same 2014 and 2017 minima, the same 2018 convergence—this would suggest that the structural coordinate evolution is universal, which is inconsistent with the anisotropic corridor picture. Identical profiles would either indicate that the two trajectories are not truly independent, or that structural evolution in the heliosheath is dominated by radial distance rather than by directional corridor structure.

Corollary. This prediction implies that the structural anisotropy of the heliosheath is detectable in the UNNS coordinates. If Voyager 1 plasma data (northward trajectory, different heliospheric corridor) were processed through the same DLCP pipeline, the resulting $\kappa_{\mathrm{conn}}(t)$ profile for velocity should show a different temporal structure than the southward Voyager 2 profile—different peak timing, different episodic minima, possibly different amplitude range—while remaining within the FULL class.

9.4 Prediction 3: Non-Identical Boundary Approach Signatures

Section 8.1 identified a structural convergence region in the 2017–2018 windows: all three FULL observables simultaneously approach their structural minima, with coordinated declines in κ_{conn} and tailDom preceding the heliopause. This is predicted to be a general feature of heliosheath trajectories, but not a universal template.

Proposition 9.3 (Non-Identical Boundary Approach). *Independent trajectories will exhibit boundary approach behaviour characterised by:*

(i) continuous variation of $m(L(t))$ toward zero in the pre-crossing interval;

(ii) systematic but trajectory-dependent *evolution of κ_{conn} and* tailDom*;*

(iii) absence of identical temporal profiles across trajectories.

Boundary approach is structurally detectable but geometrically non-universal.

Falsification criterion. An abrupt class transition at a physical boundary crossing with no preceding systematic decline in $m(L(t))$ or κ_{conn} over the approach interval would falsify this prediction and Proposition 3.3 simultaneously. Conversely, a completely sharp transition with no pre-crossing structural preparation in any independent traverse would indicate that the heliopause is a genuine structural discontinuity, not a convergence region.

The Voyager 1 case. Voyager 1 crossed the heliopause in August 2012 along a different corridor and at a different angle to the interstellar magnetic field. If its PLS data were available in high-resolution form and processed through the DLCP pipeline, Prediction 3 would require: a systematic decline in $\kappa_{\mathrm{conn}}(t)$ for kinematic observables in the years before August 2012, but at a different rate and from a different peak structure than Voyager 2's 2017–2018 approach. This is a directly testable, quantitatively specific prediction.

9.5 Prediction 4: Temporal Continuity as a Universal Constraint

The observed continuity of $m(L(t))$ along the Voyager 2 trajectory (Proposition 3.1) is not a statement about Voyager 2 specifically. It follows from the geometric interpretation of margin as a boundary-distance functional in a manifold with continuous local structure. A manifold with discontinuous boundary distances would not be a valid geometric space in the sense of [LocalGeom2025].

Proposition 9.4 (Continuity as a Universal Geometric Constraint)**.** *For any physically admissible trajectory through any slowly evolving system, the margin function $m(L(t))$ must be continuous or piecewise continuous in time, except at genuine structural boundary crossings.*

This is the strongest of the four predictions because it is not heliosphere-specific: it is a structural requirement on any trajectory in $\mathcal{M}_{\text{adm}}$. A plasma system exhibiting random discontinuities in $m(L(t))$ without physical events would not merely challenge the heliospheric interpretation—it would challenge the geometric structure of $\mathcal{M}_{\text{adm}}$ itself.

Falsification criterion. In any domain, a time series in which $m(L(t))$ undergoes sharp discontinuities at windows that share 75% of their data with the preceding window, with no physically identifiable structural cause, would falsify this prediction. The operational threshold follows from the window overlap: a 15× change in κ_{conn} between adjacent 75%-overlapping windows with no physical explanation would exceed the continuity bound.

9.6 Joint Falsifiability

The four predictions define a joint falsifiability structure for the UNNS-based trajectory model:

Table 8: Predictions and Their Independent Falsification Criteria

Prediction	**Confirmed by**	**Falsified by**
P1: Class invariance	Each observable confined to fixed class in any independent traverse	Stochastic class switching without boundary crossing
P2: Metric non-universality	Different $\kappa_{\text{conn}}(t)$ profiles across distinct heliospheric corridors	Identical profiles across structurally independent trajectories
P3: Non-identical boundary approach	Systematic pre-crossing decline in $m(L(t))$, trajectory-dependent amplitude	Abrupt crossing with no structural preparation
P4: Continuity constraint	Piecewise-continuous $m(L(t))(t)$ in any slowly evolving system	Discontinuous m without physical boundary event

The four predictions are logically independent: one can be falsified without the others. This independence is important for the programme: if P1 fails (class switching occurs) but P4 holds (continuity is preserved), the local geometry is intact but the class stability interpretation requires revision. If P4 fails, the foundational geometric interpretation of margin is challenged.

9.7 Implications If Validated

If all four predictions are validated by independent trajectories, the following consequences follow:

1. Realizability structure is not trajectory-specific. The Voyager 2 results are not an artifact of a particular path through the heliosheath; they reflect the structure of $\mathcal{M}_{\text{adm}}$ itself.

2. $\mathcal{M}_{\text{adm}}$ provides a shared structural coordinate system across physical observations. Different spacecraft tracing different paths through the same medium occupy the same manifold, with class as the shared invariant and metric coordinates as the trajectory-specific signal.

3. The heliosphere is better understood as a realization of a constrained structural manifold than as a purely geometric boundary. Different spacecraft do not merely sample different spatial regions; they trace distinct paths within a common realizability geometry.

10 Realizability Dynamics: Proposition System

This section restates Propositions 3.1–3.3 (Propositions 1–3 of Section 3) in compressed, corpus-evaluated form, and adds a synthesis statement. Each proposition is accompanied by its empirical status against the 628-run Voyager 2 corpus and a specific epistemic note.

10.1 Proposition 1 — Temporal Structural Continuity

Structural coordinates of DLCP trajectories evolve continuously or piecewise continuously, with variations attributable to identifiable physical or structural causes.

Corpus status: Confirmed. The annual κ_{conn} and tailDom time series for all four observables exhibit piecewise-continuous evolution across 11 years. Every sharp variation (the 2009 thermal peak, the 2014 and 2017 velocity collapses, the 2018 coordinated minimum) corresponds to an identifiable physical event or structural regime boundary. No coordinate undergoes a discontinuity without physical cause.

Epistemic note: Continuity is verified at the annual-mean granularity of Table 5. Window-level continuity has not been systematically tested across all 628 windows. This is an open verification task.

10.2 Proposition 2 — Dominant-Regime Persistence

DLCP trajectories remain within a dominant realizability class, with deviations confined to localised, structurally conditioned excursions. Observable representation defines the baseline regime; trajectory evolution permits limited boundary-adjacent transitions without global class change.

Corpus status: Confirmed. 96.0% of 628 runs conform to the expected dominant class. The 4.9% TAIL/GIANT exception rate for v/T/w consists entirely of high-GR (> 0.97) windows clustered near the heliopause; none arise from random stochastic fluctuations in the trajectory interior. The single velocity HARD window (2010 win 04) and two trivial density FULL windows (2009 win 02–03) are structurally explained.

Epistemic note: Dominant-regime persistence is established for one heliosheath traverse. Cross-domain and multi-trajectory generalisation has not been demonstrated.

10.3 Proposition 3 — Detectable Boundary Approach

Boundary approach is indicated by coordinated softening of structural coordinates together with the emergence of boundary-adjacent classes, signalling transition onset without requiring global regime change.

Corpus status: Partially confirmed. The 2014–2018 interval shows coordinated κ_{conn} and tailDom decline across all three FULL observables, satisfying the coordinate-softening criterion. Three GIANT windows (v: 2018 win 01–02; w: 2017 win 06) satisfy the class-emergence criterion, constituting the first observed FULL→GIANT transition onset in a UNNS trajectory. Post-crossing ISM data would be required to confirm a sustained regime change.

Epistemic note: The pre-crossing boundary approach is confirmed as an observational signature. Whether the transition continues after the heliopause into a new dominant regime (e.g., sustained GIANT or HARD) is an open empirical question.

10.4 Synthesis: Trajectories in $\mathcal{M}_{\text{adm}}$

Together, Propositions 1–3 define realizability dynamics as a continuous trajectory constrained within a dominant regime, with boundary approach expressed through coordinated structural softening and localised class excursions. Physical systems thus evolve in $\mathcal{M}_{\text{adm}}$ not as static classifications, but as regime-stable trajectories with structurally detectable transition onset.

> **Epistemic Limits (summary).** The following scope constraints apply to all results in this paper: (1) **Pre-crossing only**: post-heliopause ISM data is absent; no sustained post-crossing class change has been observed. (2) **Single traverse**: one southward heliosheath crossing; no cross-trajectory or Voyager 1 comparison is available. (3) **Density is representation-theoretic**: the HARD classification reflects PLS instrument topology, not physical plasma structure. (4) **Window-size**

> **sensitivity**: all results are specific to $\Delta = 1024$ samples; verification at alternative window sizes is pending. (5) **No cross-domain invariance**: κ_{conn} values and tail dominance ranges are not claimed to be universal across physical systems. Physical interpretations (corridor structure, anisotropy, gradient field) are inferences from structural coordinates, not direct heliosheath measurements.

11 Conclusion

This work establishes the first empirical realisation of dynamic trajectories in UNNS realizability space for a physical system. Using a DLCP-compliant reconstruction of Voyager 2 heliosheath plasma data, we show that structural coordinates (κ_{conn}, tail dominance, giant ratio, margin) evolve continuously while class membership exhibits strong—but not absolute—dominant-regime stability.

The principal result is a *dominant-class persistence law with structured boundary access*. Across 628 runs, observable-specific regimes persist at 96.0% conformance, with all deviations confined to identifiable structural conditions. TAIL and GIANT classifications appear exclusively in high-connectivity, near-boundary states and cluster in the late heliosheath phase. The detection of GIANT windows immediately prior to heliopause crossing constitutes the first observational evidence of class-level transition onset in a UNNS trajectory. This provides partial confirmation of the boundary transition mechanism proposed in Proposition 3.3.

The five propositions are evaluated as follows:

Table 9: Proposition Status Against Full Corpus

Prop.	**Claim (abbreviated)**	**Corpus status**
3.1	Temporal structural continuity	Confirmed
3.2	Dominant-regime persistence (96.0%)	Confirmed
3.3	Detectable boundary approach + GIANT onset	Partially confirmed
3.4	Trajectory regularity within class	Confirmed
3.5	Margin as forward temporal indicator	Supported

The density observable exhibits a distinct behaviour: systematic HARD fragmentation accompanied by universal Theorem 1 triggering. This is not a property of the heliosheath plasma itself but of the measurement representation, demonstrating that realizability class depends on distributional structure rather than physical quantity alone. Density thus joins TiO_2 as a canonical discrete-regime domain within the UNNS programme.

Taken together, the results shift the interpretation of realizability structure from a static classification scheme to a *dynamical phase geometry*. Physical systems do not simply occupy realizability classes; they trace trajectories that remain largely confined within dominant regimes while developing localised boundary excursions and, under appropriate conditions, undergoing partial class transitions.

In the heliosheath context, this implies that the heliopause is not a sharp structural discontinuity but is preceded by a transition layer in realizability space, detectable through coordinated softening of structural coordinates and the emergence of boundary-adjacent classes. The present dataset captures the approach to this layer; definitive confirmation of full regime transition requires post-heliopause interstellar medium data.

More broadly, the framework demonstrates that realizability space provides a unifying language for describing stability, fragmentation, and transition across physical systems. The Voyager 2 trajectory represents the first large-scale empirical mapping of such dynamics, establishing a foundation for cross-domain structural analysis within the UNNS Substrate.

Central result. Real physical systems trace trajectories in realizability space that exhibit dominant-regime persistence with structured boundary access. The Voyager 2 heliosheath traverse demonstrates: coordinated multi-variable softening preceding heliopause approach; localised FULL→GIANT class excursions as the first empirical evidence of transition onset; and systematic discrete-regime occupation of the density observable through measurement topology. The UNNS realizability manifold is not a classification tool; it is a *structural coordinate system* in which physical systems evolve according to geometric law, approaching boundaries through detectable transition layers rather than instantaneous jumps.

The UNNS Substrate is inherently dynamical: structural trajectories evolve, and boundary approach is detectable prior to transition.

A Pilot Batch: Complete Per-Window Data (STRUC-PERC-I v2.4)

The 2007-08-27 and 2008-01-01 epochs were fully processed through STRUC-PERC-I v2.4 with complete instrument output. Tables 10 through 13 report per-window results.

Table 10: Pilot Batch: Velocity Ladders

Date	**Win**	**Samples**	κ_{conn}	tailDom	GR
2007-08-27	0	0–1024	169.32	0.5642	0.9795
2007-08-27	1	256–1280	199.16	0.6271	0.9736
2007-08-27	2	512–1536	377.93	0.5767	0.9629
2007-08-27	3	768–1792	**410.65**	0.5461	0.9677
2007-08-27	4	1024–2048	*(missing: quality gate)*		
2007-08-27	5	1280–2304	366.93	0.5843	0.9844
2007-08-27	6	1536–2560	255.36	0.5460	0.9844
2007-08-27	7	1792–2816	224.09	0.4782	0.9853
2007-08-27	8	2048–3072	216.91	0.4766	0.9570
2008-01-01	0	0–1024	130.48	0.4383	0.9804
2008-01-01	1	256–1280	221.33	0.4701	0.9804
2008-01-01	2	512–1536	230.36	0.4765	0.9804

All windows: FULL_PERCOLATION. **Bold**: maximum.

Table 11: Pilot Batch: Temperature Ladders

Date	**Win**	**Samples**	κ_{conn}	tailDom	GR
2007-08-27	0	0–1024	522.08	0.6291	0.9736
2007-08-27	1	256–1280	548.41	0.5924	0.9756
2007-08-27	2	512–1536	402.98	0.5727	0.9775
2007-08-27	3	768–1792	337.52	0.5283	0.9785
2007-08-27	4	1024–2048	338.79	0.5145	0.9814
2007-08-27	5	1280–2304	319.64	0.4884	0.9697
2007-08-27	6	1536–2560	188.53	0.4201	0.9824
2007-08-27	7	1792–2816	120.01	0.3418	0.9902
2007-08-27	8	2048–3072	308.52	0.4394	0.9873
2008-01-01	0	0–1024	679.97	0.6346	0.9634
2008-01-01	1	256–1280	671.05	0.6214	0.9644
2008-01-01	2	512–1536	**728.61**	0.6006	0.9834
2008-01-01	3	768–1792	431.32	0.4991	0.9814

All windows: FULL_PERCOLATION. **Bold**: pilot-batch maximum.

Table 12: Pilot Batch: Thermal Speed Ladders

Date	**Win**	**Samples**	κ_{conn}	tailDom	GR
2007-08-27	0	0–1024	161.14	0.3310	**0.9941**
2007-08-27	1	256–1280	206.93	0.3624	0.9863
2007-08-27	2	512–1536	222.83	0.4640	0.9785
2007-08-27	3	768–1792	175.59	0.4477	0.9775
2007-08-27	4	1024–2048	176.36	0.4202	0.9775
2007-08-27	5	1280–2304	160.55	0.3971	0.9756
2007-08-27	6	1536–2560	102.81	0.3283	0.9922
2007-08-27	7	1792–2816	65.04	0.2697	0.9844
2007-08-27	8	2048–3072	165.18	0.3913	0.9814
2008-01-01	0	0–1024	259.33	0.4759	0.9832
2008-01-01	1	256–1280	252.04	0.4639	0.9871
2008-01-01	2	512–1536	**285.14**	0.4659	0.9892

All windows: FULL_PERCOLATION. **Bold**: pilot-batch maximum (GR) or κ_{conn} maximum.

Table 13: Pilot Batch: Density Ladders (all HARD_FRAGMENTATION)

Date	**Win**	**Samples**	κ_{conn}	tailDom	GR
2007-08-27	0	0–1024	N/A	0.000	0.9804
2007-08-27	1	256–1280	N/A	0.000	0.9107
2007-08-27	2	512–1536	N/A	0.000	0.8947
2007-08-27	3	768–1792	N/A	0.000	0.9091
2007-08-27	4	1024–2048	N/A	0.000	0.9091
2007-08-27	5	1280–2304	N/A	0.000	0.9444
2007-08-27	6	1536–2560	N/A	0.000	0.9630
2007-08-27	7	1792–2816	N/A	0.000	0.9636
2007-08-27	8	2048–3072	N/A	0.000	0.9444
2008-01-01	0	0–1024	N/A	0.000	0.9038
2008-01-01	1	256–1280	N/A	0.000	0.9216
2008-01-01	2	512–1536	N/A	0.000	0.7959
2008-01-01	3	768–1792	N/A	0.000	<u>0.7407</u>

All windows: HARD_FRAGMENTATION. κ_{conn} = N/A (no percolation at any κ). <u>Underline</u>: minimum GR.

B DLCP and STRUC-PERC-I Parameters

Table 14: Full Parameter Specification

Parameter	**Value**
Window size (Δ)	1024 samples
Step size (Δ_{step})	256 samples
Min. valid ratio (α)	0.95
Normalization	Raw (no transform)
STRUC-PERC-I version	v2.4
Percolation scan	$\kappa = 0 \to \kappa_{\max}$; 17-layer adaptive
Tail definition	Fraction of gap mass beyond 10× median gap
GR	Largest component / total unique ladder size
Margin $m(L)$	$\kappa_{\text{conn}}/\kappa_{\text{critical}}$ (see [LocalGeom2025])

C Data Provenance

All CDF files obtained from NASA CDAWeb (`VOYAGER2_PLS_HIRES_PLASMA_DATA_HSH`):

```
voyager2_pls_hires_plasma_data_hsh_20070827_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20080101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20090101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20100101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20110101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20120101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20130101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20140101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20150101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20160101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20170101_v01.cdf
voyager2_pls_hires_plasma_data_hsh_20180101_v01.cdf
```

Table 15: Window Counts per Epoch

Year	Windows	Notes
2007	9	Partial year (from 2007-08-27)
2008	21	
2009	12	
2010	10	
2011	21	
2012	21	
2013	24	Maximum
2014	10	
2015	10	
2016	10	
2017	11	
2018	3	Truncated (ending 2018-11-05)
Total	162	

D Reproducibility

All analyses used `voyager_ladder_pipeline.py` (DLCP-compliant) and STRUC-PERC-I v2.4. Raw ladder files, per-window STRUC-PERC-I output, and the full annual summary dataset are archived at the UNNS Substrate data repository. The initial pilot batch includes complete instrument output (layers.csv, components.csv, outliers.json, summary.json) per window.

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