Pre-Registered Predictions for the Hera Mission Using a Coupled Dynamical Framework (Quantum LiRam v1)

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Abstract

We present pre-registered probabilistic predictions for the rotational and gravitational properties of Dimorphos at the time of ESA's Hera mission arrival (2026). The predictions are generated using a minimal coupled dynamical framework incorporating internal structure, effective dissipation, and environmental interaction within the Didymos–Dimorphos binary system. All input parameters, model variants, scoring metrics, and success criteria are frozen prior to Hera data release.

1 Scope and Objective

This document defines a pre-registered predictive framework for the Hera mission. No post-hoc parameter tuning will be performed after Hera data release. All predictions are probabilistic and evaluated using predefined scoring rules.

2 Model Definition

We model Dimorphos as a coupled dynamical system:

$$\dot{x}(t) = \mathcal{D}\big(x(t); C_{\text{body}}, C_{\text{env}}(t), K\big), \tag{1}$$

where:

- C_{body} encodes internal properties (triaxiality, density, dissipation),

- $C_{\text{env}}(t)$ encodes environmental forcing (binary coupling),

- K is a scalar coupling parameter.

Energy dissipation is modeled via a nonlinear regulation term:

$$\dot{E} = \gamma A^2 g(\phi) + \epsilon, \qquad A = \frac{A_0}{1 + \alpha E}. \tag{2}$$

The parameters α and Q_{eff} represent effective dissipation properties.

3 Frozen Input Parameters

Only publicly available pre-Hera data are allowed:

- Triaxiality estimates from pre-Hera shape models

- Density and porosity ranges from literature

- Post-DART dynamical constraints

Free parameters (with wide priors):

- Q_{eff}

- α

- K

- τ (optional delay term)

Maximum number of free parameters: 4.

4 Model Variants

4.1 QL-FULL

Includes internal structure and environmental coupling.

4.2 QL-ABLATED

Identical but with $K = 0$ (no environmental interaction).

4.3 BASELINE

Standard triaxial dissipative rotation model without nonlinear regulation.

5 Predictive Outputs

5.1 O1: Rotational Regime Classification

Three exclusive classes:

- R0: Near principal-axis rotation

- R1: Moderate non-principal-axis (bounded tumbling)

- R2: Strong tumbling / chaotic regime

Probabilities $P(R0)$, $P(R1)$, $P(R2)$ are provided.

5.2 O2: Gravitational Harmonics

Predicted probability distributions for degree-2 gravity coefficients:

$$C_{22}, \quad J_2.$$

5.3 O3: Rotational Persistence Signature

Predicted decay profile or persistence of libration amplitude over observational window.

6 Scoring Protocol

- Log-score (multiclass) for O1

- Continuous Ranked Probability Score (CRPS) for O2 and O3

- 95% interval coverage validation

7 Success Criteria

QL-FULL is considered successful if:

- It outperforms BASELINE on at least two outputs,

- It outperforms QL-ABLATED on at least one output,

- Interval coverage remains between 90% and 98%.

8 Data Lock Statement

All predictions, priors, and scoring scripts will be frozen and publicly archived before Hera data release.

9 Reproducibility

A public repository will contain:

- Code for QL-FULL, QL-ABLATED, BASELINE

- Frozen prediction JSON file

- Scoring scripts