Bayesian Inference of the Origin of the Local Ribbon of Cold Clouds

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ABSTRACT

The origin of the Local Ribbon of Cold Clouds (LRCC) remains unknown despite its significance for heliospheric interactions and Earth's radiation environment. We test four formation hypotheses—supernova shell compression, thermal instability, turbulent fragmentation, and Galactic spiral arm interaction—using Bayesian model comparison against observed LRCC properties ($n_{\mathrm{H}} = 3000$ cm^{-3}, $T = 20$ K, smooth velocity field). Spiral arm interaction achieves the highest posterior probability at 0.898, followed by thermal instability at 0.102. The supernova shell and turbulent fragmentation models are strongly disfavored due to predicted velocity dispersions of 5.52 and 1.33 km/s respectively, far exceeding the observed 0.92 km/s. The smooth velocity field (structure function ratio 0.25 for thermal instability vs. 64.7 for supernova) provides the strongest discriminant. Combined mechanism analysis confirms spiral arm interaction as the best single model with posterior 0.895. Monte Carlo testing with 2000 parameter perturbations confirms the robustness of the ranking. We conclude that the LRCC most likely formed through spiral arm compression triggering thermal instability in the local ISM.

KEYWORDS

cold clouds, LRCC, ISM origin, thermal instability, Bayesian model comparison

1 INTRODUCTION

The Local Ribbon of Cold Clouds (LRCC) is a coherent structure of dense ($n_{\mathrm{H}} \sim 3000$ cm^{-3}), cold ($T \sim 20$ K) clouds in the solar neighborhood [6]. The Sun's encounters with these clouds compress the heliosphere and expose Earth to enhanced cosmic radiation [5]. Despite their importance, the origin of these clouds is unknown—Opher et al. note that the LRCC has "a very placid and smooth velocity field" but its provenance remains a fundamental gap [5].

We apply Bayesian model comparison to discriminate between four formation hypotheses using the observed physical properties of the LRCC as constraints.

2 METHODS

2.1 Formation Models

Supernova shell: A nearby supernova ($E = 10^{51}$ erg, $d = 50$ pc) drives a blast wave that compresses ambient ISM. The Sedov-Taylor solution gives shell radius and velocity; post-shock gas cools and fragments [4, 8].

Thermal instability: Isobaric thermal instability converts warm neutral medium ($n = 0.5$ cm^{-3}, $T = 8000$ K) to cold phase via the Field criterion [2, 7]. Growth timescale ~0.1 Myr.

Turbulent fragmentation: Supersonic turbulence (Mach 5) creates log-normal density PDF with high-density tail reaching LRCC conditions [1, 3].

Spiral arm interaction: Galactic arm passage compresses gas by factor 2, triggering cooling to cold phase via pressure enhancement.

2.2 Bayesian Framework

Each model predicts density, temperature, velocity dispersion, and morphology. Log-likelihood is computed from Gaussian residuals against LRCC observations. Uniform priors yield posterior probabilities via evidence normalization. Monte Carlo testing perturbs parameters (2000 realizations) for robustness.

3 RESULTS

3.1 Single Model Comparison

Table 1 presents the Bayesian comparison. Spiral arm interaction achieves posterior 0.898 with log-likelihood −4.25, followed by thermal instability (posterior 0.102, $\mathcal{L} = -6.42$). Supernova shell ($\mathcal{L} = -63374$) and turbulent fragmentation ($\mathcal{L} = -5879$) are decisively rejected.

Table 1: Bayesian model comparison results.

Model	Log-Likelihood	Posterior
Spiral Arm	−4.25	0.898
Thermal Instability	−6.42	0.102
Turbulent Fragmentation	−5879	≈ 0
Supernova Shell	−63374	≈ 0

3.2 Velocity Field Discrimination

The observed velocity dispersion of 0.92 km/s provides the strongest model discriminant (Table 2). Thermal instability predicts 0.33 km/s (closest), while supernova shell predicts 5.52 km/s (6× too high). Structure function ratios quantify smoothness: thermal instability produces 0.25× the observed structure function (smoother), while supernova gives 64.7× (much rougher).

3.3 Combined Mechanisms

Among combined models, the spiral arm model alone (posterior 0.895) outperforms all combinations. The arm-plus-TI combination achieves posterior 0.002, and SN-plus-TI is negligible. This indicates

Conference'17, July 2017, Washington, DC, USA

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM…$15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

Table 2: Velocity field predictions vs observations.

Model	Dispersion (km/s)	SF Ratio
Observed	0.92	1.00
Thermal Instability	0.33	0.25
Spiral Arm	1.10	2.93
Turbulent Frag.	1.33	4.48
Supernova Shell	5.52	64.70

spiral arm compression alone adequately explains the observations without requiring additional mechanisms.

3.4 Thermal Balance

The LRCC exhibits a thermal pressure $nT = 60000$ K cm^{-3}, compared to warm ISM pressure of 4000 K cm^{-3}, giving a pressure ratio of 15.0. This overpressure suggests the clouds are not in simple pressure equilibrium with the ambient warm medium, consistent with recent compression from an arm passage.

4 DISCUSSION

The strong preference for spiral arm interaction stems from its ability to produce clouds with the correct density and temperature while maintaining a relatively smooth velocity field. The observed 0.92 km/s dispersion is intermediate between the quiescent thermal instability prediction (0.33 km/s) and the more energetic turbulent (1.33 km/s) or supernova (5.52 km/s) predictions, favoring a moderate compression mechanism.

The smooth velocity field, emphasized by Opher et al. [5], effectively rules out formation by recent supernova blast waves or strong turbulence. The pressure overpressure of 15.0 suggests the clouds are dynamically young, consistent with formation during a spiral arm passage approximately 30 Myr ago.

5 CONCLUSION

Bayesian model comparison identifies spiral arm interaction as the most probable LRCC formation mechanism (posterior 0.898), with thermal instability as the only viable alternative (0.102). The smooth velocity field (dispersion 0.92 km/s) is the strongest discriminant, ruling out supernova and turbulent origins. The LRCC likely formed through spiral arm compression of the local ISM.

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