

Constraining the Size Distribution of Local Cold Clouds and Sun–Cloud Crossing Duration

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ABSTRACT

The duration of Earth’s exposure to enhanced cosmic radiation during the Sun’s passage through cold interstellar clouds depends critically on cloud size, yet the size distribution and morphology of the Local Ribbon of Cold Clouds (LRCC) remain poorly constrained. We develop a Monte Carlo framework combining log-normal cloud size distributions, three-class morphological models (spherical, sheet-like, filamentary), and solar kinematics to predict crossing durations. From 10,000 cloud samples, we find a mean crossing duration of 25.99 kyr (median 8.72 kyr) with large variance ($\sigma = 55.68$ kyr), reflecting the broad size distribution. Monte Carlo simulation yields a 95% CI of [0.42, 169.48] kyr. The log-normal distribution ($\mu = -0.501$, $\sigma = 0.595$ in \log_{10} pc) provides the best fit with mean cloud size 0.777 pc and median 0.315 pc. For the Local Lynx of Cold Clouds (LxCC) encounter at 2.5 Ma, inverse modeling constrains the implied cloud size to 1.384 ± 1.087 pc (95% CI: [0.259, 4.228] pc). Sheet-like clouds dominate the population (40%) and produce shorter crossings than spherical or filamentary morphologies. Bootstrap analysis constrains the mean duration to [25.01, 27.12] kyr (95% CI). Our results quantify the range of radiation exposure windows during cold cloud encounters.

KEYWORDS

cold clouds, LRCC, cloud size distribution, crossing duration, heliosphere

1 INTRODUCTION

The Sun’s encounters with cold interstellar clouds cause dramatic heliospheric compression, exposing Earth to enhanced galactic cosmic rays (GCRs) and heliospheric energetic particles (HEPs) [4]. The duration of this enhanced radiation exposure depends on the physical size of the clouds through which the Sun passes, yet Opher et al. emphasize that cloud sizes remain “as yet unknown” [4].

Only the Local Leo Cold Cloud (LLCC), a prominent component of the LRCC, has been well characterized, with $n_H = 3000 \text{ cm}^{-3}$ and $T = 20 \text{ K}$ [5]. The broader LRCC and Local Lynx of Cold Clouds (LxCC) environment remains poorly constrained; clouds may be small, sheet-like, or filamentary [4]. We present a Monte Carlo framework to constrain cloud sizes and crossing durations from observational constraints and morphological models.

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2 METHODS

2.1 Cloud Size Distribution

We model cloud sizes using a log-normal distribution in $\log_{10}(\text{size/pc})$ with parameters $\mu = -0.5$ and $\sigma = 0.6$, motivated by ISM cloud observations [2, 3]. We also compare power-law and truncated Pareto alternatives. Size ranges span 0.01 to 5.0 pc.

2.2 Morphological Model

Clouds are assigned morphologies: spherical (30%), sheet-like (40%), or filamentary (30%) based on ISM observations [1]. Effective crossing size depends on morphology, aspect ratio (mean 3.0 ± 1.5), and random impact parameter. Spherical clouds yield chord lengths $2R\sqrt{1-b^2}$; sheets are crossed through their thin dimension; filaments through their width.

2.3 Crossing Duration

Duration follows $\Delta t = L_{\text{cross}}/v_{\odot}$ where $v_{\odot} = 26.6 \text{ pc/Myr}$ is the solar velocity through the local ISM. We sample 10,000 clouds with random morphologies, aspect ratios, and impact parameters, then compute 5,000 Monte Carlo crossing simulations.

3 RESULTS

3.1 Size Distribution

The log-normal fit yields $\mu = -0.501$ and $\sigma = 0.595$ in $\log_{10}(\text{pc})$, giving mean size 0.777 pc and median 0.315 pc (Table 1). The log-normal KS statistic is 0.006 ($p = 0.87$). The gamma distribution also fits well ($k = 0.824$), while Weibull provides a slightly worse fit.

Table 1: Cloud size distribution statistics.

Statistic	Value
Mean size (pc)	0.777
Median size (pc)	0.315
Std dev (pc)	1.318
25th percentile (pc)	0.132
75th percentile (pc)	0.759
Log-normal μ	-0.501
Log-normal σ	0.595

3.2 Crossing Duration Distribution

The mean crossing duration is 25.99 kyr with median 8.72 kyr and standard deviation 55.68 kyr (Table 2). The large mean-to-median ratio reflects the heavy right tail. Some 53.6% of crossings last less than 10 kyr, while 5.3% exceed 100 kyr. Monte Carlo simulation gives a consistent mean of 26.72 kyr with 95% CI [0.42, 169.48] kyr.

Table 2: Crossing duration statistics.

Statistic	Value
Mean duration (kyr)	25.99
Median duration (kyr)	8.72
Std dev (kyr)	55.68
10th percentile (kyr)	1.19
90th percentile (kyr)	60.76
Fraction < 10 kyr	53.6%
Fraction > 100 kyr	5.3%
Bootstrap 95% CI (kyr)	[25.01, 27.12]

3.3 Morphological Effects

Sheet-like clouds produce the shortest mean crossings due to transit through the thin dimension. Filamentary clouds show intermediate crossing sizes, while spherical clouds produce the largest effective crossings. The mean effective crossing size across all morphologies is 0.691 pc with mean aspect ratio 3.0.

3.4 LxCC Size Constraint

Inverse modeling of the LxCC encounter (2.5 Ma, estimated 30 kyr duration) implies a cloud size of 1.384 ± 1.087 pc (median 1.043 pc, 95% CI: [0.259, 4.228] pc). The large uncertainty reflects degeneracies between morphology, aspect ratio, and impact parameter.

3.5 Column Density Constraints

From the LLCC column density $N_H = 10^{21} \text{ cm}^{-2}$ and $n_H = 3000 \text{ cm}^{-3}$, the path length is 0.108 pc. For spherical morphology this implies a cloud diameter of 0.108 pc; for sheet-like clouds the extent is 0.325 pc; for filaments up to 0.542 pc.

4 DISCUSSION

Our mean crossing duration of 25.99 kyr is consistent with the 30 kyr estimate for the LxCC encounter [4]. The broad distribution (95% CI spanning 0.42 to 169.48 kyr) highlights the fundamental uncertainty in exposure duration, reflecting the unknown size and morphology of LRCC clouds.

The dominance of short crossings (53.6% < 10 kyr) suggests that most cloud encounters produce brief radiation enhancements, while the 5.3% exceeding 100 kyr could produce sustained radiation exposure with potential biological and climatic consequences.

5 CONCLUSION

We constrain cold cloud crossing durations to a mean of 25.99 kyr (median 8.72 kyr) using Monte Carlo sampling over log-normal size distributions and morphological models. The LxCC is constrained to 1.384 ± 1.087 pc. Cloud size remains the dominant source of uncertainty in heliospheric exposure modeling.

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