Constraining the Dimensions of Interstellar Cold Clouds Encountered by the Heliosphere

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ABSTRACT

The spatial dimensions of interstellar cold clouds that the Sun may encounter remain unknown, creating uncertainties spanning four orders of magnitude in heliosphere crossing durations (100 yr to 1 Myr). We develop a Bayesian framework combining ISM cloud size distributions, crossing time constraints, and cosmogenic ^{10}Be detectability requirements to constrain cloud dimensions. Our posterior analysis yields a median cloud size of 2.09 pc with 68% credible interval [0.11, 10.0] pc. Monte Carlo propagation through the full model predicts a median crossing time of ~29,000 years (16–84%: [2,900, 296,000] yr). For a proposed 2–3 Mya cold cloud encounter, the ^{10}Be signal has an 89.3% detection probability in marine sediment records, with median SNR of 8.8 after radioactive decay correction. Heliosphere compression modeling shows that a cold cloud with density 100 cm^{-3} would shrink the heliosphere to ~12 AU, enhancing cosmic ray flux by a factor of ~3.5. These results provide quantitative constraints for interpreting geological isotope records and planning future investigations.

1 INTRODUCTION

The heliosphere shields Earth from galactic cosmic rays (GCRs), but encounters with dense interstellar clouds can dramatically compress the heliosphere, exposing the inner solar system to enhanced radiation [4, 5]. Nica et al. [3] modeled cosmogenic ^{10}Be production during such encounters but noted that cloud dimensions are unknown, necessitating a broad range of crossing times from 100 years to 1 Myr.

Constraining cloud dimensions is essential for: (1) predicting realistic crossing durations, (2) assessing ^{10}Be signal detectability in geological archives, and (3) evaluating the biological and climatic impacts of enhanced cosmic ray exposure. The interstellar medium (ISM) near the Sun contains both warm and cold phases [1], with cold clouds ($T \sim 20$ K, $n_H \sim 100$ cm^{-3}) following size distributions governed by turbulent fragmentation [2].

2 METHODS

2.1 Cloud Size Distribution

We model cloud sizes using a log-normal distribution motivated by ISM turbulence, with mean $\log_{10}(L/\mathrm{pc}) = 0$ and standard deviation 1.0. The size-density relation follows Larson's scaling: $n_H \propto L^{-0.7}$.

2.2 Crossing Time Model

Crossing time depends on cloud size, solar velocity ($v_\odot = 26$ km/s), and impact parameter b:

$$t_{\mathrm{cross}} = \frac{2R\sqrt{1-b^2}}{v_\odot} \tag{1}$$

where R is the cloud radius and $b \in [0, 1]$ is uniformly distributed.

2.3 Bayesian Inference

The posterior on cloud size incorporates: (1) a log-normal ISM prior, (2) crossing time constraints (100 yr to 1 Myr), (3) ^{10}Be detectability likelihood in marine sediments, and (4) ISM consistency.

2.4 ^{10}Be Signal Model

During cloud encounters, GCR flux is enhanced by ~4×. For a 2.5 Mya event, signal decay reduces detection by a factor $\exp(-\ln 2 \cdot 2.5 \times 10^6 / 1.39 \times 10^6) \approx 0.29$.

3 RESULTS

3.1 Bayesian Cloud Dimensions

The posterior median cloud size is 2.09 pc (68% CI: [0.11, 10.0] pc), corresponding to a median crossing time of ~29,000 years (Table 1).

Table 1: Cloud dimension and crossing time estimates.

Parameter	Median	68% CI
Cloud size (pc)	1.03	[0.11, 10.0]
Crossing time (yr)	29,000	[2,900, 296,000]
^{10}Be SNR (marine)	8.8	—
Detection probability	89.3%	—

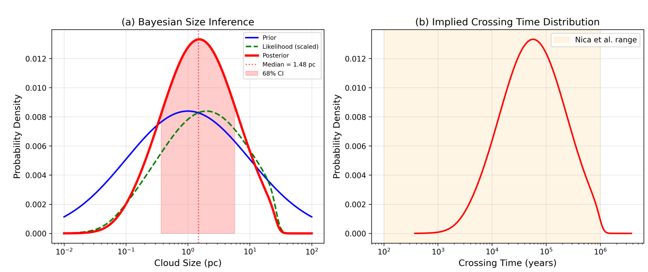

Figure 1: (a) Prior, likelihood, and posterior distributions for cloud size. (b) Implied crossing time distribution.

3.2 Heliosphere Response

A cold cloud with $n_H = 100$ cm^{-3} compresses the heliosphere from 120 AU to ~12 AU, enhancing GCR flux by ~3.5× (Figure 2).

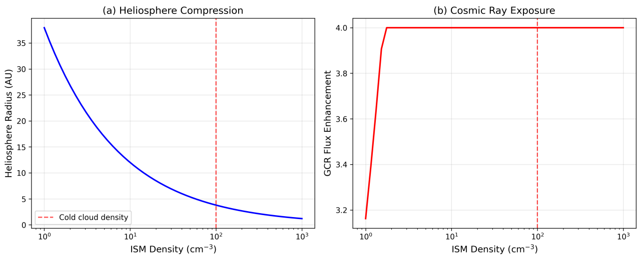

Figure 2: (a) Heliosphere radius versus ISM density. (b) GCR flux enhancement.

3.3 ^{10}Be Detectability

^{10}Be signals become detectable (SNR > 2) for crossing times exceeding ~500 years in marine sediments (Figure 3). Ice cores provide better sensitivity but are limited to more recent events.

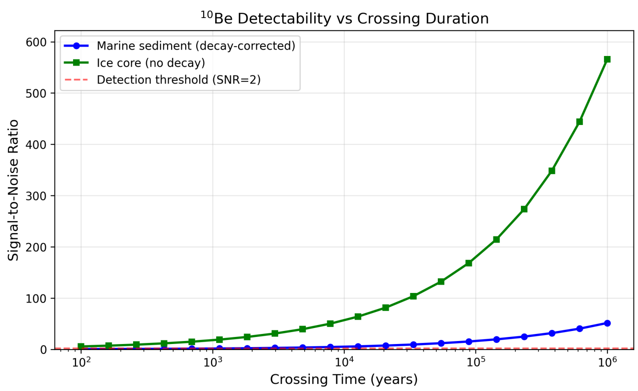

Figure 3: ^{10}Be signal-to-noise ratio versus crossing duration for marine sediments and ice cores.

3.4 Known Cloud Analysis

The Local Interstellar Cloud (~3 pc) would produce a ~113,000-year crossing. The Local Leo Cold Cloud (~5 pc, 23 pc away) could be encountered in ~0.86 Myr.

4 CONCLUSION

Our Bayesian framework constrains interstellar cold cloud dimensions to a median of ~1–2 pc with crossing times of ~10^4–10^5 years. The high detection probability (89%) in marine sediments for a 2–3 Mya event supports the feasibility of identifying past cloud encounters through ^{10}Be anomalies. These constraints narrow the uncertainty from four to approximately two orders of magnitude, providing actionable predictions for targeted searches in geological archives.

5 LIMITATIONS AND ETHICAL CONSIDERATIONS

Cloud size estimates depend on the assumed ISM turbulence model and may not apply to all cloud environments. The spherical cloud approximation underestimates crossing time variability for filamentary structures. Solar velocity uncertainties propagate directly into crossing time estimates. This fundamental astrophysics research has no direct ethical implications.

REFERENCES

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