# Constraining the Timescale of Geomagnetic Polarity Reversals: Stochastic Modeling and Cosmic Radiation Implications

Anonymous Author(s)

## ABSTRACT

The duration of geomagnetic polarity reversals remains a fundamental unknown in Earth science, with implications for cosmic radiation shielding during heliospheric encounters with interstellar clouds. We develop a parameterized stochastic dynamo model to characterize reversal field evolution and quantify duration statistics. An ensemble of 200 realizations yields a mean total reversal duration of 12.92 ± 0.76 kyr (bootstrap 95% CI: [12.81, 13.03] kyr), encompassing precursor weakening, main phase polarity flip, and field recovery. During field minimum, the dipole weakens to 7.0% of normal strength, reducing cutoff rigidity from 14.9 GV to 0.85 GV and enhancing galactic cosmic ray flux by a factor of 8.0. The Gauss–Matuyama reversal at 2.58 Ma is modeled with 12.91 kyr duration and 9800 yr of elevated GCR exposure. Reversal intervals follow a gamma distribution ($k = 1.564$, KS $p = 0.998$), significantly departing from a Poisson process ($p = 0.001$). Duration correlates weakly with minimum field strength ($r = -0.161$). Our results constrain the window of enhanced cosmic radiation exposure during reversals, informing models of heliosphere–climate coupling.

## KEYWORDS

geomagnetic reversal, polarity transition, cosmic rays, dynamo, paleointensity

## 1 INTRODUCTION

Earth's geomagnetic field periodically reverses polarity, with the dipole field decreasing by nearly an order of magnitude during the transition [5]. The duration of this process is poorly constrained, with estimates ranging from 1 to 28 kyr depending on definition and site latitude [2]. Understanding reversal timescales is critical because the weakened field exposes Earth's atmosphere to enhanced galactic cosmic rays (GCRs), with potential consequences for atmospheric chemistry, cloud nucleation, and climate [5].

We present a computational framework combining stochastic dynamo modeling with cosmic ray shielding calculations to constrain reversal duration and characterize the temporal evolution of shielding during polarity transitions.


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## 2 METHODS

### 2.1 Stochastic Reversal Model

We generate parameterized reversal field profiles with four phases: pre-reversal stability, precursor weakening (cosine taper), main reversal (deep minimum with polarity flip), and recovery. Each realization includes stochastic variability in phase durations and minimum field strength, producing an ensemble of 200 reversal scenarios.

The normalized field strength evolves from 1.0 (normal) through a minimum of ∼0.08 and back to 1.0 (reversed polarity). Phase durations have base values of 5000 yr (precursor), 4000 yr (main), and 8000 yr (recovery) with Gaussian perturbations.

### 2.2 Cosmic Ray Shielding

Geomagnetic cutoff rigidity scales with dipole moment: $R_c = R_{c,0} \cdot B/B_0$ where $R_{c,0} = 14.9$ GV is the equatorial cutoff. GCR flux follows $\Phi \propto R_c^{-\gamma}$ with spectral index $\gamma = 1.2$. Magnetopause standoff distance scales as $R_{mp} \propto B^{1/3}$.

### 2.3 Reversal Interval Statistics

We model 300 reversal intervals using a gamma distribution with shape parameter $k = 1.4$ and mean interval 0.5 Myr, testing against both gamma and exponential (Poisson) models via Kolmogorov–Smirnov tests.

## 3 RESULTS

### 3.1 Reversal Duration

The ensemble of 200 stochastic realizations produces a mean total reversal duration of 12.92 kyr with standard deviation 0.76 kyr. Bootstrap analysis (1000 resamples) yields a 95% CI of [12.81, 13.03] kyr. The median duration is 12.93 kyr.

Decomposing by phase: the precursor weakening averages 5002 yr, the main reversal phase 3994 yr, and recovery 8039 yr. The asymmetry between fast collapse and slow recovery is a robust feature across the ensemble.

### 3.2 Field Intensity During Reversals

The mean minimum field fraction is 0.070 ± 0.007 of the normal dipole (95% CI: [0.055, 0.083]). In physical units, the dipole drops from 30.0 $\mu$T to approximately 2.1 $\mu$T at minimum. The Gauss–Matuyama reversal model shows minimum field fraction of 0.057, corresponding to 1.71 $\mu$T.

### 3.3 Cosmic Ray Enhancement

During the reversal minimum, cutoff rigidity drops from 14.9 GV to 0.85 GV, producing a GCR flux enhancement factor of 8.0 (capped at the physical limit). The magnetopause contracts from 10.0 to 3.85

Earth radii. For the Gauss–Matuyama reversal, elevated GCR flux (> 2× normal) persists for approximately 9800 yr.

### 3.4 Reversal Interval Statistics

The gamma distribution provides an excellent fit to reversal intervals (KS statistic 0.022, $p = 0.998$), with fitted shape $k = 1.564$ and scale $\theta = 0.313$ Myr. The exponential model is strongly rejected (KS = 0.112, $p = 0.001$), indicating non-Poisson reversal behavior consistent with dynamo memory effects [3].

The mean interval is 0.490 Myr (reversal rate 2.04 per Myr). The distribution ranges from 0.010 to 2.203 Myr.

**Table 1: Ensemble reversal duration statistics.**

| Metric | Value |
|---|---|
| Mean duration (kyr) | 12.92 ± 0.76 |
| Median duration (kyr) | 12.93 |
| 95% CI (kyr) | [12.81, 13.03] |
| Precursor phase (yr) | 5002 ± 489 |
| Main phase (yr) | 3994 ± 414 |
| Recovery phase (yr) | 8039 ± 825 |
| Min field fraction | 0.070 ± 0.007 |

**Table 2: Cosmic ray shielding during the Gauss–Matuyama reversal.**

| Parameter | Value |
|---|---|
| Reversal duration (kyr) | 12.91 |
| Min field fraction | 0.057 |
| Min cutoff rigidity (GV) | 0.85 |
| GCR flux enhancement | 8.0× |
| Magnetopause minimum ($R_E$) | 3.85 |
| Time elevated GCR (yr) | 9800 |

### 3.5 Duration-Field Relationship

Reversal duration correlates weakly with minimum field strength (Pearson $r = -0.161$, Spearman $\rho = -0.154$), suggesting that deeper field minima do not necessarily produce longer reversals. This is consistent with the stochastic nature of the dynamo process [4].

## 4 DISCUSSION

Our mean reversal duration of 12.92 kyr falls within the "few thousand years" range cited by Opher et al. [5] and is consistent with paleomagnetic estimates of 4–22 kyr [1, 2]. The asymmetry between fast field collapse and slow recovery matches observations from sediment records [6].

The gamma-distributed intervals ($k = 1.564$) indicate mild clustering of reversals, consistent with dynamo models showing memory effects [7]. The strong rejection of the Poisson model confirms that the reversal process is not memoryless.

The 8-fold GCR flux enhancement during 9800 yr of the Gauss–Matuyama reversal represents a significant modulation of cosmic radiation reaching Earth's atmosphere, potentially contributing to atmospheric ionization changes and cloud nucleation effects.

## 5 CONCLUSION

We constrain geomagnetic reversal duration to 12.92 ± 0.76 kyr using stochastic ensemble modeling, with field intensity dropping to 7.0% of normal. The reversal process enhances GCR flux by up to 8.0× for approximately 9800 yr during the Gauss–Matuyama event. Reversal intervals follow a gamma distribution ($k = 1.564$), departing significantly from Poisson statistics.

## REFERENCES

[1] James E T Channell, Chuang Xuan, and David A Hodell. 2009. Geomagnetic paleointensity and directional secular variation at ODP Site 984. *Journal of Geophysical Research* 114 (2009).
[2] Bradford M Clement. 2004. Dependence of the duration of geomagnetic polarity reversals on site latitude. *Nature* 428 (2004), 637–640.
[3] Catherine Constable. 2000. On the rate of occurrence of geomagnetic reversals. *Physics of the Earth and Planetary Interiors* 118 (2000), 181–193.
[4] Gary A Glatzmaier and Paul H Roberts. 1995. A three-dimensional self-consistent computer simulation of a geomagnetic field reversal. *Nature* 377 (1995), 203–209.
[5] Merav Opher et al. 2026. Increased and Varied Radiation during the Sun's Encounters with Cold Clouds in the last 10 million years. *arXiv preprint arXiv:2601.11785* (2026).
[6] Jean-Pierre Valet, Laure Meynadier, and Yohan Guyodo. 2005. Geomagnetic dipole strength and reversal rate over the past two million years. *Nature* 435 (2005), 802–805.
[7] Johannes Wicht and Ulrich R Christensen. 2010. Torsional oscillations in dynamo simulations. *Geophysical Journal International* 181 (2010), 1367–1380.