

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

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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 $30.0 \mu\text{T}$ to approximately $2.1 \mu\text{T}$ at minimum. The Gauss–Matuyama reversal model shows minimum field fraction of 0.057, corresponding to $1.71 \mu\text{T}$.

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

117 at the physical limit). The magnetopause contracts from 10.0 to 3.85
 118 Earth radii. For the Gauss–Matuyama reversal, elevated GCR flux
 119 (> 2× normal) persists for approximately 9800 yr.
 120

121 3.4 Reversal Interval Statistics

122 The gamma distribution provides an excellent fit to reversal inter-
 123 vals (KS statistic 0.022, $p = 0.998$), with fitted shape $k = 1.564$ and
 124 scale $\theta = 0.313$ Myr. The exponential model is strongly rejected
 125 (KS = 0.112, $p = 0.001$), indicating non-Poisson reversal behavior
 126 consistent with dynamo memory effects [3].
 127

128 The mean interval is 0.490 Myr (reversal rate 2.04 per Myr). The
 129 distribution ranges from 0.010 to 2.203 Myr.
 130

131 **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

144 **Table 2: Cosmic ray shielding during the Gauss–Matuyama
 145 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

157 3.5 Duration-Field Relationship

158 Reversal duration correlates weakly with minimum field strength
 159 (Pearson $r = -0.161$, Spearman $\rho = -0.154$), suggesting that deeper
 160 field minima do not necessarily produce longer reversals. This is
 161 consistent with the stochastic nature of the dynamo process [4].
 162

163 4 DISCUSSION

164 Our mean reversal duration of 12.92 kyr falls within the “few thou-
 165 sand years” range cited by Opher et al. [5] and is consistent with
 166 paleomagnetic estimates of 4–22 kyr [1, 2]. The asymmetry between
 167 fast field collapse and slow recovery matches observations from
 168 sediment records [6].
 169

170 The gamma-distributed intervals ($k = 1.564$) indicate mild clus-
 171 tering of reversals, consistent with dynamo models showing mem-
 172 ory effects [7]. The strong rejection of the Poisson model confirms
 173 that the reversal process is not memoryless.
 174

175 The 8-fold GCR flux enhancement during 9800 yr of the Gauss–
 176 Matuyama reversal represents a significant modulation of cosmic
 177 radiation reaching Earth’s atmosphere, potentially contributing to
 178 atmospheric ionization changes and cloud nucleation effects.
 179

180 5 CONCLUSION

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