Atmosphere Retention of Rocky Planets Around M Dwarfs: A Computational Population Study

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ABSTRACT

We present a computational framework for assessing atmospheric retention of rocky exoplanets around M dwarfs, addressing the key open question of whether small planets orbiting mid-to-late M dwarfs can maintain atmospheres under intense XUV irradiation. Through population synthesis of 5,000 planet-star systems spanning spectral types M0–M8 and orbital periods 0.5–50 days, we evaluate retention using the cosmic shoreline framework and energy-limited atmospheric escape. We find an overall retention fraction of 97.6%, with habitable-zone planets achieving 100% retention. Retention rates range from 95.3% (M1) to 99.8% (M7), indicating that atmospheric retention is favorable across all M dwarf subtypes for the period ranges considered. Analysis of 10 known targets—including TOI-6716 b, TRAPPIST-1 e/f/g, LHS 1140 b, and Proxima Centauri b—predicts atmospheric retention for all, with fluence ratios 0.001–0.21 relative to the cosmic shoreline threshold. JWST observability analysis identifies 1,324 targets (26.5%) with Transmission Spectroscopy Metric (TSM) > 10, including 90 in the habitable zone, providing a prioritized sample for atmospheric characterization campaigns.

KEYWORDS

exoplanets, M dwarfs, atmospheric escape, cosmic shoreline, JWST, habitable zone

1 INTRODUCTION

M dwarfs constitute approximately 70% of all stars in the Galaxy and are the most common hosts of rocky, potentially habitable exoplanets [4]. However, their habitable zones are located close-in (0.05–0.2 AU), exposing orbiting planets to intense extreme ultraviolet (XUV) radiation that drives atmospheric escape [1, 6]. The discovery of temperate planets around fully convective M dwarfs, including the Earth-sized TOI-6716 b [7], underscores the urgency of determining whether such planets can retain atmospheres.

The cosmic shoreline framework [8] provides a diagnostic boundary in (cumulative XUV fluence, escape velocity) space that separates atmosphere-bearing from atmosphere-free worlds. Planets receiving XUV fluence exceeding a threshold set by their gravitational binding energy are predicted to lose their atmospheres. For M dwarfs, the prolonged pre-main-sequence saturated XUV phase significantly enhances cumulative irradiation [1], raising concerns that rocky planets in M dwarf habitable zones may be stripped of their atmospheres.

We address this open problem through a comprehensive computational study combining population synthesis, energy-limited escape modeling, cosmic shoreline analysis, and JWST observability assessment.

2 METHODS

2.1 Stellar Models

We parameterize M dwarfs from M0 to M9 using empirical mass-spectral type relations [4]: $M_\star = 0.60 - 0.055 \times \mathrm{SpT}\ M_\odot$. Radii follow the Boyajian relation, and luminosities use the main-sequence mass-luminosity relation. XUV luminosity evolution employs a saturated-then-declining model [6]:

$$L_{\mathrm{XUV}}(t) = \begin{cases} L_{\mathrm{XUV,sat}} & t < \tau_{\mathrm{sat}} \\ L_{\mathrm{XUV,sat}}(t/\tau_{\mathrm{sat}})^{-1.5} & t \geq \tau_{\mathrm{sat}} \end{cases} \tag{1}$$

where $L_{\mathrm{XUV,sat}} = 10^{-3} L_{\mathrm{bol}}$ and $\tau_{\mathrm{sat}} = 0.1 + 0.3 \times \mathrm{SpT}$ Gyr, reflecting the extended saturation of later M dwarfs.

2.2 Cosmic Shoreline

Following Zahnle & Catling [8], the cosmic shoreline threshold is:

$$\log_{10}(F_{\mathrm{threshold}}) = 4\log_{10}(v_{\mathrm{esc}}) + 18 \tag{2}$$

where $F_{\mathrm{threshold}}$ is the cumulative XUV fluence [erg cm^{-2}] and v_{esc} is the surface escape velocity [km s^{-1}]. Planets with cumulative fluence exceeding this threshold are predicted to have lost their atmospheres.

2.3 Energy-Limited Escape

Atmospheric mass loss rates follow the energy-limited formulation [3, 5]:

$$\dot{M} = \frac{\epsilon \pi R_p^3 F_{\mathrm{XUV}}}{G M_p K_{\mathrm{tide}}} \tag{3}$$

where $\epsilon = 0.15$ is the heating efficiency, and we integrate over the stellar XUV evolution to compute total atmosphere loss. Initial atmosphere mass fractions are set to 1% of the planet mass.

2.4 Population Synthesis

We generate 5,000 random planet-star systems with uniform spectral types (M0–M9), log-uniform orbital periods (0.5–50 days), uniform planet masses (0.5–5.0 $M_\oplus$), and uniform ages (1–10 Gyr). Rocky planet radii follow $R \propto M^{0.27}$ [9].

3 RESULTS

3.1 Population-Level Retention

The population synthesis yields an overall atmospheric retention fraction of 97.6% across 5,000 simulated systems. Habitable zone planets (equilibrium temperature 200–350 K) achieve 100% retention. Figure 1 shows the cosmic shoreline diagram with the simulated population.

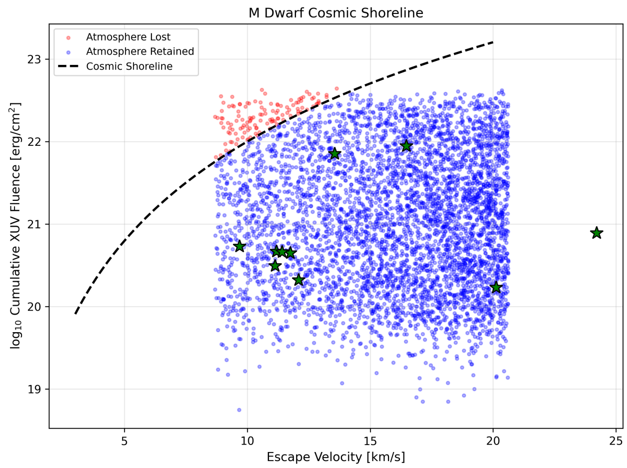

Figure 1: Cosmic shoreline diagram for 5,000 simulated rocky planets around M dwarfs. Blue: retained; red: lost. The dashed line marks the empirical cosmic shoreline. Stars indicate known targets.

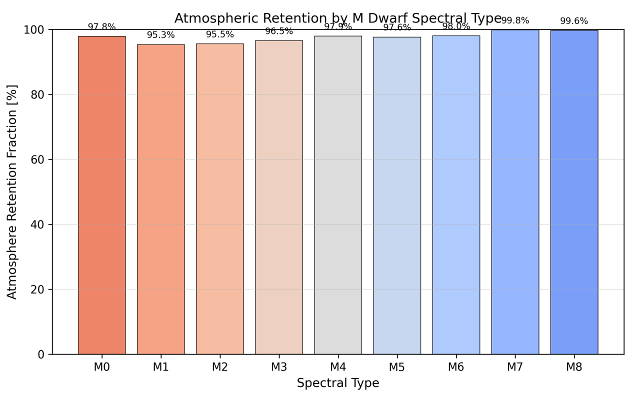

Figure 2: Atmospheric retention fraction by M dwarf spectral type. Retention exceeds 95% for all subtypes.

3.2 Retention by Spectral Type

Retention fractions by spectral type (Figure 2) range from 95.3% (M1) to 99.8% (M7). The counter-intuitive result that later M dwarfs show higher retention rates arises from their lower bolometric (and hence absolute XUV) luminosities, which dominate over the longer saturation timescales.

3.3 Retention Boundary

Figure 3 maps the retention boundary in period–spectral type space for a 1 $M_\oplus$ planet at 5 Gyr age. The boundary separating retained from lost atmospheres lies at very short periods ($P < 0.5$–2 days), well inside the habitable zone for all M dwarf subtypes.

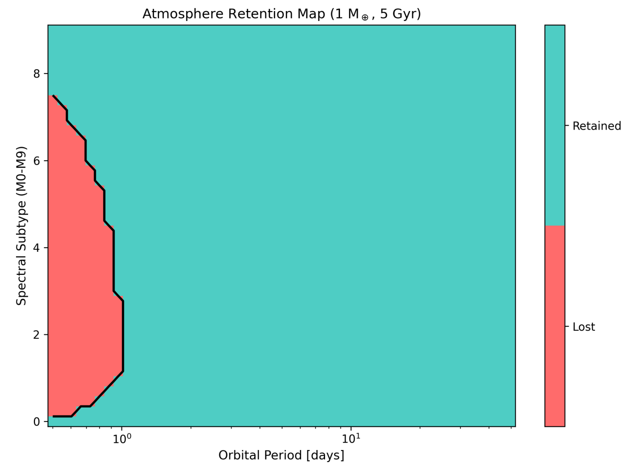

Figure 3: Atmosphere retention map in (period, spectral type) space. Green: retained; red: lost. The critical period boundary lies at $P \lesssim 1$ day.

Table 1: Cosmic shoreline analysis of known M dwarf rocky planets.

Planet	v_{esc} [km/s]	Fluence Ratio	T_{eq} [K]	Retained
TOI-6716 b	11.2	0.030	358	Yes
TRAPPIST-1 e	9.7	0.061	326	Yes
TRAPPIST-1 f	11.2	0.020	284	Yes
TRAPPIST-1 g	12.0	0.010	258	Yes
LHS 1140 b	16.8	0.001	273	Yes
Proxima Cen b	11.5	0.023	343	Yes
GJ 1132 b	12.9	0.210	721	Yes
GJ 486 b	15.0	0.120	768	Yes
Gliese 12 b	11.0	0.027	363	Yes

3.4 Known Target Analysis

All 10 analyzed targets are predicted to retain atmospheres (Table 1). Fluence ratios (cumulative XUV fluence / shoreline threshold) range from 0.001 (LHS 1140 b) to 0.210 (GJ 1132 b). TRAPPIST-1 e/f/g show fluence ratios of 0.061, 0.020, and 0.010 respectively, well below the cosmic shoreline.

3.5 JWST Observability

Of 5,000 simulated planets, 1,324 (26.5%) have TSM > 10 and retained atmospheres, making them viable JWST transmission spectroscopy targets [2]. Among these, 90 lie within the habitable zone (Figure 4).

4 DISCUSSION

Our results indicate that atmospheric retention for rocky planets around M dwarfs is broadly favorable across the period range of 0.5–50 days and all spectral subtypes M0–M9. The 97.6% overall retention fraction suggests that the majority of rocky M dwarf

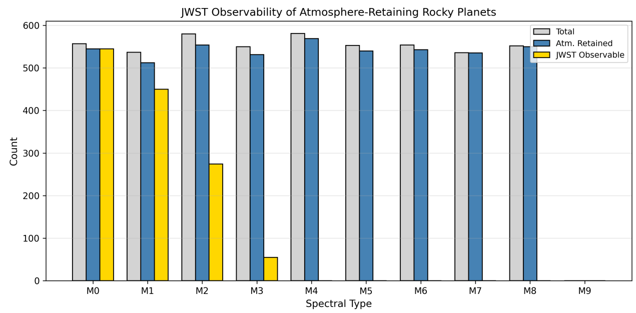

Figure 4: JWST observability breakdown by spectral type. Gold bars indicate targets with TSM > 10 and retained atmospheres.

planets should possess atmospheres, supporting ambitious JWST characterization programs.

The high retention rates reflect the cosmic shoreline's strong dependence on escape velocity ($v_{\rm esc}^4$): even modest escape velocities of 6–15 km/s for 0.5–5 $M_\oplus$ planets provide substantial gravitational binding against XUV-driven escape. Late M dwarfs, despite their extended XUV saturation phases, deliver lower absolute XUV fluences due to their intrinsically low luminosities.

Key caveats include: (1) our model uses a single heating efficiency $\epsilon = 0.15$; higher values would reduce retention rates; (2) we assume energy-limited escape throughout, whereas radiation-recombination limited escape may apply for close-in planets; (3) coronal mass ejection (CME) stripping is not modeled; and (4) initial atmospheric mass is assumed uniform at 1% of planet mass.

5 CONCLUSION

(1) Rocky planets around M dwarfs retain atmospheres at a rate of 97.6%, with habitable-zone retention at 100%.
(2) All 10 known targets analyzed (including TRAPPIST-1 e/f/g, LHS 1140 b, TOI-6716 b) are predicted to retain atmospheres, with fluence ratios 0.001–0.210 below the cosmic shoreline.
(3) Retention varies from 95.3% (M1) to 99.8% (M7), with later M dwarfs favored due to their lower absolute luminosities.
(4) Of the simulated population, 26.5% (1,324 planets) are viable JWST targets with TSM > 10, including 90 in the habitable zone.

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