Baryon Crowding Relation (BCR): Empirical Mapping of Anomalous Galactic and Cluster Velocities

Abstract

We present the **Baryon Crowding Relation (BCR)**, a new empirical scaling law linking three-dimensional baryonic mass distribution to galaxy rotation velocities. Unlike the Radial Acceleration Relation (RAR), which correlates total observed acceleration with baryonic content, BCR isolates the geometric crowding of baryons as the sole input, revealing that anomalous velocities are encoded strictly in mass distribution rather than requiring unseen components. Applied to the SPARC galaxy sample and cluster-scale data, BCR achieves median RMS deviations of order 0.07 dex, matching or exceeding RAR performance while offering a more physically transparent mapping.

In parallel, we introduce an **AI bootstrap framework**: a portable prompt architecture that enables large language models (LLMs) to execute the BCR formula autonomously. This framework reproduces results across independent AI agents, accelerates iteration on geometric assumptions and parameters, and permits conceptual probing of the relation's structure. By combining empirical scaling and AI-driven reproducibility, this work provides both a new observational tool and a methodology for rapid theoretical refinement in galaxy dynamics.

1. Introduction

Galaxy rotation curves remain among the most stringent empirical tests of gravitation and baryon dynamics on kiloparsec scales. Observations consistently show a mismatch between the luminous mass profiles of galaxies and their measured orbital velocities, motivating two broad explanatory frameworks: **non-baryonic dark matter** and **modified gravity**. In recent years, the **Radial Acceleration Relation (RAR)** has emerged as a tight empirical correlation linking observed acceleration to baryonic acceleration, underscoring a deeper coupling between visible matter and galactic dynamics.

Despite its utility, the RAR conflates two aspects of baryonic structure: total mass and spatial distribution. Here we report a new empirical relation — the **Baryon Crowding Relation (BCR)** — that disentangles these contributions by focusing solely on **three-dimensional baryon crowding**: the degree to which mass is geometrically concentrated at each radius. BCR directly maps enclosed baryonic mass profiles to predicted velocities without invoking dark matter or modified dynamics. Its accuracy across both galaxies and clusters suggests that geometric crowding alone encodes the dominant signal behind rotation anomalies.

Beyond the relation itself, we describe a **novel AI bootstrap methodology** for deriving and validating such empirical laws. By encoding the BCR kernel into portable natural-language prompts, large language models can execute the full calculation pipeline — from baryonic inputs to velocity predictions — without bespoke codebases. This enables rapid replication, cross-agent verification, and iterative refinement of model assumptions (e.g., disk flare, bulge geometry). The approach thus serves both as a reproducibility tool and as a conceptual probe: isolating where anomalous signals originate and clarifying which aspects warrant theoretical explanation.

In the sections that follow, we define the BCR, detail its implementation and empirical performance, describe the AI bootstrap framework, and discuss its implications for both observational analysis and theoretical development in galaxy dynamics.

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2. The Baryon Crowding Relation (BCR)

2.1 Definition and Motivation

The Baryon Crowding Relation (BCR) is an empirical mapping from three-dimensional baryonic mass distribution to predicted circular velocity. It is motivated by the observation that galaxy rotation anomalies scale not only with the total baryonic mass but with how that mass is geometrically concentrated at each radius. BCR formalizes this by introducing a crowding parameter that accounts for enclosed mass and radial geometry, producing a closed-form velocity prediction without invoking dark matter or modified dynamics. Enclosed mass provides a practical proxy for local geometric baryon density, which is the fundamental parameter that BCR seeks to characterize.

2.2 Core Relation (Updated Parameters)

We define the baryon crowding parameter C at radius r as:

$$ C(r) = \frac{G \cdot M_{\text{bar}}(r)}{r^2 \cdot g_\dagger} $$

where:

- G is the gravitational constant (4.30091×10^{-6} kpc (km/s)^2 / M_\odot),
- $M_{\text{bar}}(r)$ is the enclosed baryonic mass at radius r ,
- $g_\dagger$ is the characteristic acceleration scale:
- **Galaxies:** $g_{\dagger,gal} = 8.6 \times 10^{-11}$ m/s^2
- **Clusters:** $g_{\dagger,cl} = 1.771 \times 10^{-9}$ m/s^2
- r is in kiloparsecs for galaxies and converted appropriately for clusters.

The kernel employs a **continuous interior–exterior mapping** with soft-pivot control parameter:

- $x_0 = 0.28$

The BCR boost factor $\nu(C)$ is then defined as:

$$ \nu(C) = \sqrt{1 + 4 \cdot C^{-\alpha}} - 1 $$

with $\alpha = 5.0$ for galaxy-scale fits.

Predicted circular velocity:

$$ v_{\text{BCR}}(r) = \sqrt{\nu(C) \cdot \frac{G \cdot M_{\text{bar}}(r)}{r}} $$

This formulation applies consistently to galaxies and clusters, with domain-specific $g_\dagger$ values ensuring proper scaling.

2.3 Data and Implementation

We evaluate BCR using the SPARC galaxy sample (175 disk galaxies) and extend the same kernel to cluster-scale data from X-COP. Disk geometries are implemented as **conical-cylinder flares** with spherical bulges. For clusters, gas profiles (in Mpc) are combined with hydrostatic mass profiles (in kpc, converted to Mpc) and processed via the same kernel using the cluster-specific $g_\dagger$.

2.4 Results

Across the SPARC sample, BCR achieves median |dex| residuals of \~0.055 and RMS residuals of \~0.074 dex in predicted velocity, with bias consistent with zero. Newtonian baryons (without boost) yield \~0.125 |dex| and \~0.169 RMS dex. Approximately 64% of galaxies achieve RMS-dex $\leq$ 0.10 (versus 18% for Newtonian baryons). Cluster tests show comparable scaling behavior when normalized with $g_{\dagger,cl}$, supporting the universality of the relation.

2.5 Interpretation

The unity between galaxy-scale RAR and cluster-scale cRAR has historically been unclear; the two relations do not naturally fall on a single continuous curve. The BCR framework changes this: by expressing the anomaly purely in terms of geometric baryon distribution, both galaxies and clusters align on different segments of the same crowding curve. This establishes a direct scale relationship across domains that was not evident in prior formulations.

The BCR's success implies that anomalous rotation signatures are encoded in **baryonic geometry alone**. This isolates the empirical signal to a purely geometric origin, narrowing the scope for subsequent theoretical interpretation: any viable explanation must reproduce the observed crowding-velocity mapping.\ \ While this signal isolation naturally invites theoretical speculation about the physical origin of galaxy velocity anomalies, the present paper remains strictly empirical and does not pursue those theoretical implications.

All supporting materials — including velocity charts for all 175 SPARC galaxies and 12 X-COP clusters, per-object and ensemble dex performance tables (Excel format), a master-curve plot unifying both domains, the complete bootstrap protocol, **and the full raw data sets** (SPARC enclosed mass and radius for blind testing with corresponding velocity observations, plus equivalent data for all 12 X-COP clusters) — are provided in the Appendix for reference and reproducibility. These appendices also outline data licensing and cite the original SPARC and X-COP sources to ensure transparency. Appendix A contains galaxy plots; Appendix B cluster plots; Appendix C the unified master-curve; Appendix D raw data formats and bootstrap instructions. Finally, while the unified scaling revealed by BCR invites future theoretical and observational tests, this paper maintains its empirical scope, deferring such exploration to subsequent work.