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Keywords: Astrophysics; Planetary Formation; Galactic Chemical Evolution; Metallicity; Exoplanets

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Galactic Metallicity as a Driver of Giant Exoplanet Clustering

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Abstract: We investigate the theoretical connection between galactic chemical evolution processes and the spatial distribution of giant exoplanets. Using a combined approach that integrates core accretion theory with galactic-scale metallicity gradients, we develop a framework to understand how cosmic-scale processes might influence planetary formation efficiency. Our model incorporates stellar feedback mechanisms, planetary migration, and destruction processes within a galactic context. We derive theoretical predictions for observable correlation patterns and discuss the physical mechanisms that could link galactic evolution to planetary demographics. The framework provides testable hypotheses for understanding the large-scale organization of planetary systems within galactic environments.

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1. Introduction

The diversity of exoplanetary systems reveals complex relationships between stellar properties and planetary architectures [22]. Among stellar parameters, metallicity emerges as a particularly significant factor governing giant planet formation, with observational studies consistently showing enhanced occurrence rates around metal-rich stars [1,11]. This metallicity-planet correlation suggests that the chemical composition of protoplanetary disks plays a fundamental role in determining planetary system outcomes.

Galactic chemical evolution models demonstrate significant spatial and temporal variations in stellar metallicity across galactic disks [5,17]. These variations arise from complex interplay between star formation, stellar feedback, gas dynamics, and mixing processes operating over gigayear timescales. The resulting metallicity gradients create chemically distinct regions within galaxies, potentially establishing preferential environments for different types of planetary formation.

This work explores the theoretical foundations for connecting galactic-scale metallicity distributions with observable patterns in giant exoplanet demographics. We develop a framework that links established core accretion theory [10,18] with galactic chemical evolution processes, investigating how cosmic-scale phenomena might manifest in planetary system statistics.

The central hypothesis examines whether enhanced metallicity regions within galactic disks create preferential formation environments for massive planets, potentially leading to detectable spatial correlations in large planetary samples. We focus on giant planets due to their strong metallicity dependence and relative ease of detection, making them ideal tracers of chemical evolution effects.

2. Theoretical Framework

2.1. Core Accretion in Chemical Context

Giant planet formation through core accretion depends critically on the solid material available in protoplanetary disks [3,19]. The probability of forming a planet with mass M_p at galactic position $\vec{r}$ and time t can be expressed as:

$$P(M_p|\vec{r},t) = \frac{A(\vec{r},t)}{M_\oplus}\left(\frac{M_p}{M_\oplus}\right)^{-\alpha} \exp\left(-\frac{M_p}{M_{\rm cut}(\vec{r},t)}\right) \quad (1)$$

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where $A(\vec{r}, t)$ is a normalization factor, α is the power-law index from observational studies [6,9], and M_{cut} represents the characteristic mass scale above which planet formation becomes increasingly difficult.

The metallicity dependence enters through the cutoff mass:

$$M_{\text{cut}}(\vec{r}, t) = M_{\oplus} \left(\frac{Z(\vec{r}, t)}{Z_{\odot}} \right)^{\beta} \left(\frac{\tau_{\text{disk}}(\vec{r}, t)}{\tau_{\text{ref}}} \right)^{-\delta} \tag{2}$$

Here $Z(\vec{r}, t)$ is the local metallicity, τ_{disk} is the disk lifetime, and β, δ are parameters determined by core accretion physics. The reference scales are $Z_{\odot} = 0.0134$ and $\tau_{\text{ref}} = 3 \times 10^6$ yr.

Dimensional Analysis: The probability density $P(M_p|\vec{r}, t)$ must have dimensions $[M]^{-1}$ to ensure proper normalization over mass. The normalization factor $A(\vec{r}, t)$ is dimensionless, while the exponential cutoff maintains dimensional consistency since M_p/M_{cut} is dimensionless. The metallicity ratio $Z/Z_{\odot}$ and time ratio $\tau_{\text{disk}}/\tau_{\text{ref}}$ are both dimensionless, ensuring M_{cut} has dimensions of mass.

2.2. Galactic Chemical Evolution

The evolution of metallicity in galactic disks follows a reaction-diffusion equation incorporating star formation, stellar nucleosynthesis, and gas dynamics [2,16]:

$$\frac{\partial Z}{\partial t} + \vec{v}_{\text{gas}} \cdot \nabla Z = D_{\text{turb}} \nabla^2 Z + S_{\text{yield}}(\vec{r}, t) - \frac{Z}{\tau_{\text{astration}}} - \Lambda_{\text{feedback}} \tag{3}$$

The stellar feedback term incorporates metal return from evolved stars:

$$\Lambda_{\text{feedback}} = \frac{1}{\tau_{\text{ret}}} \cdot \frac{1}{\rho_{\text{gas}}(\vec{r}, t)} \int_0^t \psi(\vec{r}, t') \int_{M_{\text{min}}}^{M_{\text{max}}} \phi(M_*) \eta_{\text{eject}}(M_*, t - t') Z_{\text{yield}}(M_*) dM_* dt' \tag{4}$$

where $\psi(\vec{r}, t')$ is the star formation rate density, $\phi(M_*)$ is the initial mass function, η_{eject} is the ejection efficiency, and Z_{yield} is the metal yield fraction.

Dimensional Verification: The star formation rate density has dimensions $[M][L]^{-3}[T]^{-1}$, the IMF has dimensions $[M]^{-1}$, gas density has dimensions $[M][L]^{-3}$, and the return timescale has dimensions $[T]$. The feedback term therefore has dimensions:

$$[\Lambda_{\text{feedback}}] = \frac{[T]^{-1} \cdot [M][L]^{-3}[T]^{-1} \cdot [M]^{-1} \cdot [T]}{[M][L]^{-3}} = [T]^{-1} \tag{5}$$

Since metallicity Z is dimensionless, $\partial Z/\partial t$ has dimensions $[T]^{-1}$, confirming that all terms in Equation 3 are dimensionally consistent.

2.3. Planetary Migration and Survival

Planetary migration significantly affects the final distribution of giant planets [10,21]. Type I migration operates on timescales:

$$\tau_{\text{mig,I}} = \frac{1}{C} \left(\frac{M_*}{M_p} \right) \left(\frac{M_*}{\Sigma_{\text{gas}} a^2} \right) \left(\frac{H}{a} \right)^2 \frac{1}{\Omega} \tag{6}$$

where C is the migration coefficient, $H = c_s/\Omega$ is the disk scale height, and $\Omega = \sqrt{GM_*/a^3}$ is the orbital frequency.

Type II migration occurs when planets open gaps in the disk:

$$\tau_{\text{mig,II}} = \frac{a^2}{\nu_{\text{visc}}} \tag{7}$$

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Dimensional Check: For Type I migration, the mass ratios M_*/M_p and geometric ratios H/a are dimensionless. The term $M_*/(\Sigma_{\text{gas}}a^2)$ has dimensions $[M]/([M][L]^{-2}[L]^2) = 1$ (dimensionless). The orbital frequency Ω has dimensions $[T]^{-1}$, so $\tau_{\text{mig,I}}$ correctly has dimensions $[T]$.

The spatial distribution of planets evolves according to:

$$\frac{\partial n_p}{\partial t} + \nabla \cdot (n_p \vec{v}_{\text{stellar}}) = \Gamma_{\text{form}} - \Gamma_{\text{mig}} - \Gamma_{\text{destruction}} \tag{8}$$

where n_p is the planet number density, Γ_{form} is the formation rate, $\Gamma_{\text{mig}} = n_p/\tau_{\text{mig}}$ is the migration loss rate, and $\Gamma_{\text{destruction}} = n_p/\tau_{\text{dest}}$ accounts for planetary destruction through stellar encounters [12,15].

3. Clustering Theory

3.1. Overdensity Field

We define the planetary overdensity field as:

$$\delta_p(\vec{r}) = \frac{n_p(\vec{r})}{\bar{n}_p} - 1 \tag{9}$$

where $n_p(\vec{r})$ is the local number density and $\bar{n}_p$ is the mean galactic density. Both quantities have dimensions $[L]^{-3}$, ensuring δ_p is dimensionless.

The two-point correlation function characterizes spatial clustering:

$$\xi(r) = \langle \delta_p(\vec{r}_1)\delta_p(\vec{r}_2) \rangle \quad \text{with } r = |\vec{r}_1 - \vec{r}_2| \tag{10}$$

3.2. Linear Perturbation Analysis

For small perturbations, the growth equation becomes [8,14]:

$$\frac{\partial \delta_p}{\partial t} = \gamma_{\text{met}}\delta_Z + \gamma_{\text{grav}}\delta_p - \gamma_{\text{diff}}\nabla^2\delta_p \tag{11}$$

The metallicity coupling strength is:

$$\gamma_{\text{met}} = \frac{\beta}{\tau_{\text{form}}}\left(\frac{Z(\vec{r},t)}{Z_\odot}\right)^{\beta-1} \tag{12}$$

Dimensional Analysis: The formation timescale τ_{form} has dimensions $[T]$, making γ_{met} have dimensions $[T]^{-1}$. Since δ_Z and δ_p are dimensionless, the first term $\gamma_{\text{met}}\delta_Z$ has dimensions $[T]^{-1}$. The gravitational growth coefficient γ_{grav} also has dimensions $[T]^{-1}$, while the diffusion coefficient γ_{diff} has dimensions $[L]^2[T]^{-1}$, ensuring the Laplacian term $\nabla^2\delta_p$ yields dimensions $[T]^{-1}$.

4. Physical Constraints

4.1. Thermodynamic Limits

The Jeans mass establishes the minimum scale for gravitational instabilities [13]:

$$M_{\text{Jeans}} = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2} \tag{13}$$

For typical protoplanetary disk conditions ($T \approx 100$ K, $\rho \approx 10^{-10}$ g cm^{-3}):

$$M_{\text{Jeans}} \approx 0.02M_\oplus\left(\frac{T}{100\text{ K}}\right)^{3/2}\left(\frac{\rho}{10^{-10}\text{ g cm}^{-3}}\right)^{-1/2} \tag{14}$$

Clustering occurs when the characteristic planet mass exceeds the Jeans mass in the relevant density regime.

4.2. Diffusion and Mixing Scales

The characteristic diffusion length during chemical evolution is [4]:

$$L_{\text{diff}} = \sqrt{D_{\text{turb}} t_{\text{chem}}} \tag{15}$$

For typical galactic values ($D_{\text{turb}} \sim 10^{28}$ cm^2 s^{-1}, $t_{\text{chem}} \sim 10^8$ yr):

$$L_{\text{diff}} \approx 1.8 \text{ kpc} \left(\frac{D_{\text{turb}}}{10^{28} \text{ cm}^2 \text{ s}^{-1}} \right)^{1/2} \left(\frac{t_{\text{chem}}}{10^8 \text{ yr}} \right)^{1/2} \tag{16}$$

Clustering signatures persist when the correlation scale exceeds the diffusion scale.

5. Theoretical Predictions

5.1. Correlation Function Form

Our framework suggests a correlation function:

$$\xi(r) = \xi_0 \left(\frac{r}{r_0} \right)^{-\gamma} \exp\left(-\frac{r}{r_{\text{cut}}} \right) \tag{17}$$

The amplitude scaling with planetary mass follows:

$$\xi_0(M_p) = \xi_{\text{ref}} \left(\frac{M_p}{M_\oplus} \right)^{\alpha_{\text{mass}}} \tag{18}$$

where $\alpha_{\text{mass}} = \beta(\alpha - 1)$ connects mass dependence to metallicity sensitivity.

5.2. Environmental Dependence

Clustering strength varies across galactic environments:

$$\xi_0(R_{\text{gal}}) = \xi_{\text{center}} \exp\left(-\frac{R_{\text{gal}}}{R_{\text{scale}}} \right) \tag{19}$$

reflecting the exponential metallicity decline with galactocentric radius observed in spiral galaxies [20].

6. Model Parameters and Estimates

Table 1. Physical Parameter Estimates.

Parameter	Symbol	Typical Range
Formation timescale	τ_{form}	$10^6 - 10^7$ yr
Migration coefficient	C	0.5 – 2.0
Metal return timescale	τ_{ret}	$10^7 - 10^8$ yr
Destruction timescale	τ_{dest}	$10^8 - 10^9$ yr
Chemical evolution time	t_{chem}	$10^8 - 10^9$ yr
Metallicity exponent	β	1.0 – 1.5
Mass function slope	α	1.2 – 1.4

7. Observational Implications

7.1. Statistical Signatures

Large-scale surveys might reveal several observational signatures:

Spatial Correlations: Positive correlations between local stellar metallicity and giant planet occurrence rates on scales of 10-100 pc, detectable through statistical analysis of samples with $\gtrsim 10^4$ well-characterized systems.

Environmental Trends: Systematic variations in planetary system architectures across different galactic regions, potentially indicating metallicity-driven formation processes.

Temporal Evolution: Clustering strength should correlate with stellar age and galactic chemical evolution history, providing tests of the theoretical framework.

7.2. Observational Requirements

Testing these predictions requires:

- Sample sizes $\gtrsim 10^4$ planetary systems with accurate mass determinations
- Precise three-dimensional stellar positions and proper motions
- Homogeneous metallicity measurements across the sample
- Understanding of local galactic chemical evolution history

Current and future surveys such as GAIA [7], TESS, and ground-based radial velocity programs may provide the necessary data for testing these theoretical predictions.

8. Discussion and Limitations

8.1. Model Assumptions

Our theoretical framework incorporates several important assumptions:

Stellar Feedback: We assume a constant metal return timescale τ_{ret}, neglecting variations with stellar mass and metallicity that could affect the chemical evolution [16].

Migration Processes: The migration timescales represent simplified approximations, neglecting planet-planet interactions, eccentricity evolution, and detailed disk thermodynamics.

Scale Separation: The approach assumes clear separation between galactic-scale ($\sim$ kpc) and planetary system-scale ($\sim$ AU) processes, which may not hold in all environments.

8.2. Scope of Validity

The theoretical framework is expected to be valid for:

- Giant planets with masses $M_p \gtrsim 0.1$ Jupiter masses
- Galactic environments with metallicity $0.1Z_\odot < Z < 3Z_\odot$
- Timescales longer than individual disk lifetimes ($t \gtrsim 10^7$ yr)
- Spatial scales larger than typical stellar cluster sizes ($r \gtrsim 10$ pc)

9. Future Directions

Future theoretical developments could include:

- Three-dimensional galactic chemical evolution models with improved spatial resolution
- Magnetohydrodynamic effects on disk structure and planet formation
- Long-term dynamical evolution of planetary systems in galactic contexts
- Variable stellar feedback efficiency depending on local environment

Numerical simulations combining galactic evolution codes with planetary formation models will be essential for testing and refining the theoretical predictions presented here.

10. Conclusions

We have developed a theoretical framework linking galactic chemical evolution to giant exoplanet spatial distribution patterns. The key contributions include:

Physical Coupling: Mathematical connections between galactic metallicity gradients and planetary formation efficiency through established core accretion theory.

Migration and Survival: Incorporation of planetary migration timescales and destruction mechanisms within a galactic context.

Statistical Framework: Clustering formalism providing testable relationships between correlation parameters and physical processes.

Observational Predictions: Specific predictions for correlation functions and environmental dependencies that can be tested with large exoplanet surveys.

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The framework establishes a conceptual bridge between galactic astrophysics and planetary formation theory. Future observational studies will determine whether the predicted clustering represents genuine physical phenomena or requires modification of the underlying theoretical assumptions.

Author and Paper Context and Future Implications

This article is published as a preprint for public dissemination and feedback from the scientific community. The author plans to submit this work or future versions to academic journals. This proposal and previous drafts have been shared with several scientists for initial feedback, whose valuable comments are incorporated to strengthen the research. If you would like to contribute with suggestions or comments, please contact me at bautista.baron@proton.me. Collaboration with the scientific community is fundamental to the development of this work, and I appreciate any input. Furthermore, I would like to thank those who wish to collaborate in the extension of this work; this paper is a preliminary model, and anyone interested in developing and publishing an expanded version would be of great help to the dissemination and future of the project.

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