A Possible Dynamical Origin for the Vertical Metallicity Gradient in the Galactic Bulge (Postprint)

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Abstract

Research has found that even during the long-term slow evolution of the Milky Way, a vertical metallicity gradient may persist in its bulge. This result contradicts earlier studies which suggested that the long-term slow evolutionary process in the Milky Way' s bulge would erase any existing chemical abundance gradients. This finding was obtained through an N-body numerical simulation model of the Milky Way' s thin disk, which can self-consistently form a boxy/peanut-shaped bulge via the disk' s bar instability and buckling instability, and combined with a chemo-dynamical model, analyzes the evolution of chemical abundances in the Milky Way' s bulge. In this evolutionary model, an initial radial metallicity gradient (-0.3 dex/kpc) is assumed; through long-term slow evolution, the bulge component develops a vertical metallicity gradient in agreement with observations. One possible explanation is that the metallicity distribution of the galactic disk underwent a "two-step" evolutionary process during long-term slow evolution. First, metal-poor particles originating at larger initial radii develop larger radial velocity dispersions during radial mixing; then, through the evolution of the bulge' s buckling instability, the vertical velocity dispersion eventually reaches a roughly constant ratio to the radial velocity dispersion (approximately 0.8). This mechanism enables metal-poor particles to occupy larger vertical extents during evolution, thus establishing the vertical metallicity gradient of the bulge.

The bulge metallicity evolution mechanism revealed by this simple chemo-dynamical model of the Milky Way bulge should also be present in more sophisticated bulge evolution models. Additionally, the chemo-dynamical model is used to discuss observational controversies in the bulge, such as the origin of multiple "peaks" in the metallicity distribution function, as well as certain limitations in the model construction.

Full Text

Preamble

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A Possible Dynamical Origin of the Vertical Metallicity Gradient in the Milky Way Bulge

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Abstract: Recent studies have revealed that a vertical metallicity gradient may persist in the Galactic bulge even during the long-term secular evolution of the Milky Way. This finding challenges earlier views that such slow evolution would erase any pre-existing chemical abundance gradients. Using an N-body numerical simulation of a Milky Way thin disk that self-consistently forms a boxy/peanut bulge through bar and buckling instabilities, combined with a chemo-dynamical model, we analyze the chemical evolution of the Galactic bulge.

In this evolutionary model, an initial radial metallicity gradient of −0.3 dex/kpc is adopted. Through long-term secular evolution, the bulge region develops a vertical metallicity gradient consistent with observations. A plausible explanation is that the disk' s metallicity distribution undergoes a "two-step" evolutionary process. First, metal-poor particles from larger initial radii acquire greater radial velocity dispersion during radial mixing. Subsequently, due to the buckling instability of the bulge, the vertical velocity dispersion maintains a roughly constant ratio to the radial velocity dispersion (approximately 0.8). This mechanism allows metal-poor particles to occupy a larger vertical extent during evolution, thereby establishing the bulge' s vertical metallicity gradient.

The metallicity evolution mechanism revealed by this simple Milky Way bulge dynamical model should also operate in models incorporating more complex bulge evolution processes. Additionally, we discuss controversial issues in bulge observations, such as the origin of multiple "peaks"in the metallicity distribution function, as well as key limitations in model construction.

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1 Introduction

Recent observations and studies of the central bulge of the Milky Way have significantly advanced our understanding of the Galaxy' s formation and evolution. Key observational features of the Galactic center include the asymmetric parallelogram-shaped structure [**?**], cylindrical rotation in kinematics [**?**], and the X-shaped distribution of bulge stars [**?**, **?**]. These findings demonstrate that the Milky Way' s bulge originates from the long-term dynamical evolution of the disk structure itself. Using numerical simulations of Milky Way models, numerous studies have successfully reproduced the formation of a boxy/peanut bulge from the disk, with results that match observational constraints on both dynamics and morphology [**?**, **?**]. In 2010, Shen et al. [**?**] proposed a Milky Way bulge model and found, when simulating the bulge' s detailed structure, that the Galactic center does not contain a significant classical bulge. This suggests that the Milky Way is more likely a galaxy formed purely through the secular evolution of its disk [**?**].

However, some arguments challenge this secular evolution scenario, particularly the observed vertical metallicity gradient in the Galactic bulge—the phenomenon where average metallicity decreases with increasing Galactic latitude. Since long-term dynamical evolution of the Milky Way involves strong dynamical mixing through bar and buckling instabilities, many astronomers believe this process unlikely to preserve an ordered chemical abundance gradient [**?**, **?**]. To address this issue, it is necessary to incorporate chemical abundance distributions into the picture of long-term dynamical evolution and construct chemo-dynamical models to understand the formation and evolution of the vertical metallicity distribution in the Galactic bulge.

Bekki and Tsujimoto [**?**] found that in their Milky Way evolution model, when initial radial and vertical metallicity gradients were imposed within the bulge radius (approximately 2 kpc), the resulting vertical gradient in the evolved bulge was relatively flat. Subsequently, Martinez-Valpuesta and Gerhard [**?**] demonstrated that to reproduce the observed vertical metallicity gradient in the Milky Way, the initial disk must possess a metallicity gradient across the entire region involved in bar/bulge formation (i.e., within the bar' s corotation radius, about 4.5 kpc). Using this approach, their model successfully reproduced the vertical metallicity gradient in the Galactic center. Their explanation invoked the approximate conservation of Jacobi energy ($E_J = E - \Omega_p L_z$), arguing that despite strong dynamical mixing, these instability processes would not alter the relative distribution of Jacobi energies between metal-poor and metal-rich stars. Consequently, metal-poor stars initially located in the outer regions would preferentially occupy the outer bulge after mixing, while the inner regions near the disk plane would remain dominated by metal-rich stars from the center, producing an observed vertical metallicity gradient. This interpretation has not gained widespread acceptance, partly because the gravitational potential rotating with the bar (Ω_p) does not remain stable during bulge formation, violating the condition for approximate conservation of Jacobi energy. Therefore, we consider this view insufficient to explain the fundamental mechanism behind the formation of the vertical metallicity gradient in the Galactic bulge.

An alternative explanation for the vertical metallicity gradient in the Galactic bulge, first proposed by Bekki and Tsujimoto [?], suggests that the bulge did not form from a single disk but rather from the long-term secular evolution of multiple disks (thin and thick) with different metallicity distributions. Since the thick and thin disks have distinct formation and evolutionary histories, thick disk stars have lower average metallicity and greater age, along with larger vertical velocity dispersion, while thin disk stars are younger with higher average metallicity and smaller vertical velocity dispersion. The combined evolution of these two components produces a bulge structure where thick disk stars occupy a larger vertical space than thin disk stars, generating a vertical metallicity gradient. Fragkoudi et al. [?] and Di Matteo et al. [?] also used similar multi-disk N-body simulations to explain the formation of the vertical metallicity gradient. A crucial observational evidence for this view is that the metallicity distribution histogram of the Galactic bulge shows multiple peaks at different metallicities, suggesting the coevolution of multiple stellar populations in the bulge, likely originating from the thin and thick disks.

Debattista et al. [?] analyzed a different multi-disk model, arguing that initial radial velocity dispersion is the primary factor producing spatial stratification of different metallicities, while assuming identical initial vertical velocity dispersions for different disks. In their N-body simulations using five superimposed disk models, the initial radial velocity dispersion decreased with increasing metallicity (all stars in a given disk had fixed metallicity). The coevolution of these disks resulted in metal-poor disks with larger initial radial velocity dispersion occupying greater vertical space, while metal-rich disks with smaller initial radial velocity dispersion remained near the disk plane. This indicates that, in addition to vertical velocity dispersion, radial velocity dispersion may play an important or even dominant role in the evolution of metallicity distribution.

How does a radial metallicity gradient produce a vertical gradient during long-term secular evolution? And what roles do radial and vertical velocity dispersions play in metallicity evolution? Addressing these two key questions, we propose a more reasonable dynamical explanation for the vertical metallicity gradient in the Galactic bulge, building upon previous research. We first use a simple chemo-dynamical model of the Milky Way bulge to reproduce its vertical metallicity gradient (Section 2) and map the overall metallicity distribution in the model (Section 3). Based on this, we analyze the formation process of the vertical metallicity gradient in the bulge through chemo-dynamical analysis, explaining how instability processes in the secular evolution scenario can produce such an ordered feature (Section 4). Additionally, we discuss the innovative significance and potential limitations of this model (Section 5).

2 Chemo-Dynamical Model

This work employs the N-body numerical simulation model established by Shen et al. [?]. In this dynamical model of the Milky Way bulge, a disk with 1×10^6 simulation particles (scale height and length of 0.2 kpc and 1.9 kpc, respectively) undergoes a very clean long-term secular evolution process—namely, the formation of a galactic bar instability and the buckling instability of the bulge—producing results that match the dynamical distribution observed in the BRAVA survey [?]. This model can also successfully simulate other detailed structures in the Galactic bulge [?]. Building upon Shen et al.' s numerical simulation, we follow the chemo-dynamical modeling approach used by Martinez-Valpuesta and Gerhard [?, ?, ?], assigning metallicity distributions to the disk particles in the initial state and setting a radial metallicity gradient as the initial condition: $[M/H]_R = [M/H]_0 + \alpha_R \times R$, where $[M/H]$ is the metallicity of simulation particles, $[M/H]_0$ is the central metallicity distribution (0.6), α_R is the radial metallicity gradient (-0.3), and R is in kpc. The adopted initial radial metallicity gradient is a natural consequence of the "inside-out formation" scenario of galaxy evolution and falls within the observed range for high-redshift galaxies (-0.15 to -0.3) [?]. Additionally, considering that the initial disk is very thin, the initial vertical metallicity gradient would not significantly affect the evolution results, and there is no observational or theoretical evidence for a high vertical metallicity gradient in the initial thin disk. Therefore, we further simplify the model by setting the initial vertical metallicity gradient to zero.

Since we assume that simulation particles maintain constant metallicity values during evolution, the evolution of chemical distributions in our chemo-dynamical model arises entirely from the redistribution of particles due to dynamical processes. Consequently, this model can directly address how particles of different metallicities mix during the long-term secular evolution of instabilities and whether a vertical metallicity gradient can form in the bulge during this process.

3.1 Metallicity Distribution Histogram

To avoid contamination from foreground and background disk particles in bulge observations, we select particles within a galactocentric radius of $R_G < 4.5$ kpc. Figure 1 [Figure 1: see original paper] shows the metallicity distribution histograms in different regions of the model bulge. At different Galactic latitudes $b = -4^\circ$, $b = -6^\circ$, $b = -8^\circ$, and $b = -10^\circ$, we mark the mean metallicity of each region with black arrows. Figure 1a presents results at an evolution time of 2.4 Gyr, corresponding to when the internal dynamical evolution of the bulge is nearly complete, while Figure 1b shows results at 4.8 Gyr, representing longer-term stable evolution. The results indicate a vertical metallicity gradient of -0.039 dex/degree along the minor axis in the range $-8^\circ < b < -4^\circ$, consistent with the observational value of -0.04 dex/degree from Gonzalez et al. [?] and -0.05 dex/degree from Gaia-ESO [?] in the corresponding region. Furthermore, comparing metallicity gradient distributions at different evolutionary epochs shows that the gradient produced by the model is stable, suggesting that the dominant process forming the vertical metallicity gradient in the Milky Way' s long-term dynamical evolution is the instability evolution during bulge formation—namely, the bar formation instability and the buckling instability of the bulge.

Another feature evident in the histograms is their non-normal distribution. As mentioned earlier, the Galactic bulge is thought to have a formation history involving multiple disk components, with important evidence being the presence of multiple peaks in the metallicity distribution histogram at different metallicities. Although the relative proportions of peaks at metal-poor and metal-rich ends remain controversial in observations [?, ?], all show non-normal histogram distributions skewed toward the metal-rich end. This observed phenomenon is generally interpreted as evidence for the coevolution of complex structures (thin disk, thick disk, halo) in the Galactic bulge [?]. To investigate this, we employed the IDL xgaussfit program [?] to decompose the metallicity distribution histograms from our model results using a Gaussian mixture model, plotting the fitted Gaussian curves in Figure 1. Our single-disk chemo-dynamical model not only produces non-normal metallicity distribution histograms but also yields relative proportions of metal-poor and metal-rich peaks consistent with the latest results from the Blanco DECam Bulge Survey (BDBS [?]). We discuss the origin of this metal-poor peak in the Galactic bulge in Section 4.2. Since metallicity distribution histogram results from different observations still show some discrepancies [?, ?, ?], the question of whether complex structures coevolve in the Galactic bulge remains open, and the contributions from thick disk and halo components in the bulge may not be particularly prominent.

3.2 (l, b)-Metallicity Distribution

In addition to metallicity distribution histograms, we map the metallicity distribution of our simulated Galactic bulge in Galactic longitude (l) and latitude (b) coordinates (see Figure 2 [Figure 2: see original paper]). For comparison with observations, we select particles within the bulge region defined by $-10^\circ < l < 10^\circ$ and $-10^\circ < b < 10^\circ$, and at distances of 4-12 kpc from the Sun [?, ?]. The Sun is positioned at 8.5 kpc from the Galactic center, at a 20° angle from the bar' s major axis (as in Figure 1 of reference [?]). The results show that our chemo-dynamical model exhibits metallicity gradients in nearly all directions, with the outer bulge occupied by metal-poor simulation particles while the central bulge remains dominated by metal-rich particles. This trend aligns with VVV observations [?]. Furthermore, we find an asymmetric metallicity distribution in the (l, b) map, manifested as higher metallicity at $l = 5^\circ$ compared to the corresponding region at $l = -5^\circ$, also present in the observational results of Gonzalez et al. [**?**]. A reasonable explanation is that the bar' s inclination angle creates a viewing effect, where the $l > 0^\circ$ end is closer to the observer than the $l < 0^\circ$ end, causing different angular extents in the longitude direction. These features, consistent with observations, demonstrate that the chemo-dynamical evolution of the Milky Way' s bar and bulge plays a crucial role in understanding the metallicity distribution evolution in the Galaxy' s central region.

3.3 Chemo-Dynamical Relations

The dynamical properties of different metallicity populations in the Galactic bulge are also important for studying its formation and evolutionary history. Populations that have experienced long-term secular evolution of the disk should retain more disk-like characteristics, such as cylindrical rotation and lower random velocity dispersion, while populations formed through other dynamical processes (e.g., galaxy mergers, star formation) would exhibit different dynamical and chemical features, such as higher random velocity dispersion. Ness et al. [**?**] decomposed bulge stars into three main populations based on metallicity: A ([Fe/H] > 0), B ($-0.5 < [Fe/H] < 0$), and C ($-1.0 < [Fe/H] < -0.5$), plus a D population ([Fe/H] < -1.0). They found that all three main populations exhibit disk-like cylindrical rotation, but in terms of velocity dispersion distribution, metal-rich populations A and B show strong vertical gradients, while metal-poor population C shows only small differences in vertical variation. In our simulations, different metallicity populations show no significant differences in basic dynamical features (cylindrical rotation, vertical distribution gradient of velocity dispersion) except that random velocity dispersion increases with decreasing metallicity (see Figure 3 [Figure 3: see original paper]).

If the difference in random velocity dispersion distribution for metal-poor populations is indeed significant, as proposed by Ness et al. [**?**], the Galactic bulge in the metallicity range $-1.0 < [Fe/H] < -0.5$ would more likely belong to a thick disk structure with a different evolutionary history from the thin disk. However, recent work by Wylie et al. [**?**], cross-matching Ness et al.'s ARGOS data [**?**] with APOGEE observations [**?**], found that population C ($-1.0 < [Fe/H] < -0.5$) does not show as clear a velocity dispersion distribution as populations A and B. We believe the evidence supporting Ness et al.' s [**?**] conclusion that population C originates from the thick disk is not particularly strong, and different metallicity populations in the Galactic bulge may still primarily originate from the secular evolution of the thin disk.

4.1 Formation Mechanism of the Bulge' s Vertical Metallicity Gradient

Based on previous analysis and discussion, we understand that the formation of the vertical metallicity gradient in our chemo-dynamical model of the Galactic bulge originates from two types of instabilities during bulge formation, with radial and vertical velocity dispersions playing crucial roles. We analyze the radial and vertical velocity dispersion distributions of different metallicity populations at various evolutionary epochs in the model, with results shown in Figure 4 [Figure 4: see original paper]. These include the initial state at $T = 0$, the time $T = 0.6$ Gyr when the bar has formed but buckling instability has not yet begun, the buckling instability phase of bulge formation ($T = 1.8$ Gyr, near completion), and after the bulge structure has evolved to stability ($T = 4.8$ Gyr). Unlike Figure 3, here we employ a more detailed population stratification, dividing stars participating in bulge formation into five components based on metallicity: $0.3 \leq [M/H] \leq 0.6$ dex (initial radius: $0 \leq R \leq 1$ kpc), $0 \leq [M/H] \leq 0.3$ dex (initial radius: $1 \leq R \leq 2$ kpc), $-0.3 \leq [M/H] \leq 0$ dex (initial radius: $2 \leq R \leq 3$ kpc), $-0.6 \leq [M/H] \leq -0.3$ dex (initial radius: $3 \leq R \leq 4$ kpc), and $-0.9 \leq [M/H] \leq -0.6$ dex (initial radius: $4 \leq R \leq 5$ kpc), and plot the evolution of their radial and vertical velocity dispersions.

Figure 4a shows the distribution of radial velocity dispersion σ_R and vertical velocity dispersion σ_Z for different populations in the initial state within $R = 5$ kpc, represented by solid and dashed line segments of different colors. The metallicity and corresponding average velocity dispersion clearly decrease with increasing radius, characteristic of velocity dispersion distributions in typical exponential disk density models. Figure 4b shows that bar formation causes strong radial mixing of simulation particles, with radial velocity dispersion σ_R changing significantly while vertical velocity dispersion σ_Z remains nearly unchanged. At this stage, the radial velocity dispersion σ_R of metal-poor populations, particularly those entering the central 2 kpc region, increases dramatically, while that of metal-rich populations shows almost no obvious change. During the buckling instability phase of bulge formation (Figure 4c), the radial velocity dispersion σ_R of different populations does not evolve significantly, while vertical velocity dispersion σ_Z increases substantially, primarily in the central bulge region ($0 \leq R \leq 2$ kpc). The final result of bulge buckling instability evolution is that the ratio of vertical to radial velocity dispersion σ_Z/σ_R reaches a relatively stable value [**?**]. Therefore, metal-poor populations that acquired higher radial velocity dispersion σ_R during bar instability will obtain higher vertical velocity dispersion σ_Z during buckling instability, meaning these populations will occupy a larger vertical range in space.

We determine the ratio σ_Z/σ_R to be approximately 0.8, which is much higher than the theoretical value for an ideal thin disk ($\sigma_Z/\sigma_R \approx 0.3$) but reasonable in more realistic galaxy simulations (see reference [**?**]). Moreover, this ratio remains nearly stable during post-bulge formation evolution in the model (Figure 4d), indicating that the bulge’ s vertical metallicity gradient also remains stable.

We summarize the formation mechanism of the metallicity distribution in the Galactic bulge as a “two-step”process: (1) The formation of the Milky Way’s bar causes strong radial mixing, bringing metal-poor stars from larger initial radii into the central region and giving them large radial velocity dispersion σ_R. (2)

The buckling instability of bulge formation gives these metal-poor stars, which already have large radial random velocity dispersion σ_R, even larger vertical velocity dispersion σ_Z, causing them to occupy a greater vertical space, while metal-rich particles with smaller radial velocity dispersion σ_R remain near the central disk region. This process creates a vertical metallicity gradient in the bulge.

Thus, in the formation of the Galactic bulge's vertical metallicity gradient, both the radial velocity dispersion discussed by Debattista et al. [**?**] and the vertical velocity dispersion discussed by Bekki and Tsujimoto [**?**] play important roles, linked through the relatively fixed ratio established during bulge evolution. The ratio σ_Z/σ_R in the bulge indicates that while internal disk evolution affects the radial velocity dispersion distribution of each population, it also influences their final vertical velocity dispersion distribution. We believe this chemo-dynamical evolution mechanism should also exist in other long-term secular evolution models of the Milky Way.

4.2 Alternative Origin of the Metal-Poor Component in the Galactic Bulge

The Milky Way' s bulge has a very complex structure [**?**, **?**, **?**]. The origin of metal-rich stars ($[Fe/H] > -0.5$) in the Galactic bulge from the secular evolution of the thin disk is a widely accepted view. However, the origin of the metal-poor component ($[Fe/H] < -0.5$) has many competing hypotheses, including a thick disk with a different evolutionary history from the thin disk [**?**], a merger-formed "classical bulge" [**?**], and an inward-extending halo [**?**], all of which may contribute to the bulge' s metal-poor component in some way. Our model suggests that the instability evolution of the Milky Way's disk causes large-scale redistribution of its initial metallicity distribution, with a significant fraction of metal-poor bulge stars still originating from the thin disk, the same as the metal-rich component. According to our calculations, the contribution from thin-disk metal-poor stars ($[Fe/H] < -0.5$) can reach 15% near Galactic latitude $b = -8^\circ$, a non-negligible fraction in studies of the origin of metal-poor stars in the Galactic bulge. Therefore, our proposed metallicity evolution scenario for the Galactic bulge provides a new perspective on the origin of its metal-poor stellar component.

5 Summary

Through chemo-dynamical modeling of a numerical simulation of the Galactic bulge, we propose a possible formation mechanism for the vertical metallicity gradient in the Milky Way bulge. Our findings are summarized in four points:

1) Instability processes in the long-term secular evolution of the Milky Way do not cause complete random mixing of stars with different metallicities and can produce a vertical metallicity gradient in the bulge consistent with observations.

2) We propose a “two-step” evolutionary process for bulge chemical abundances to explain the formation of the vertical metallicity gradient, analyzing in detail the important roles of radial velocity dispersion σ_R, vertical velocity dispersion σ_Z, and their ratio during evolution.

3) In addition to possible contributions from the thick disk and halo, the thin disk itself is an important source of metal-poor stars ([Fe/H] < -0.5) in the Galactic bulge, with its contribution reaching approximately 15% near Galactic latitude $b = -8°$.

4) The multiple peaks in the metallicity distribution histogram of the Galactic bulge may arise from the complex dynamical evolution of a single disk with a certain metallicity distribution, not necessarily requiring multiple disks with different evolutionary histories.

Our chemo-dynamical model of the Galactic bulge has some limitations. For instance, to produce a vertical metallicity gradient consistent with observations, the model requires an initial radial metallicity gradient in the disk. However, there is currently no widely accepted conclusion about the early metallicity distribution of the Milky Way. Additionally, some details of the bulge’ s metallicity distribution produced by the model are difficult to explain, such as the lack of X-shaped structure in metal-poor bulge particles [**?**] and the formation of a positive radial metallicity gradient near the disk plane observed by APOGEE [**?**]. To highlight the effects of dynamical evolution, we employed a relatively simple modeling approach, which may indeed fail to match observations perfectly. Future work will require further optimization of this modeling, such as improving the initial chemical distribution model and incorporating dark halo particles in the numerical simulation. Furthermore, this “two-step” evolutionary process of the Galactic bulge should also exist in other long-term secular evolution models of the Milky Way, and we can apply this analytical method to more complex formation and evolution models of the Galactic bulge to obtain more reasonable conclusions.

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Note: Figure translations are in progress. See original paper for figures.